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FINAL REPORT: MEASURING SURFACE AND DEEP BODY TEMPERATURES OF DOLPHINS IN THE EASTERN TROPICAL PACIFIC: IS THERMAL STRESS ASSOCIATED WITH CHASE AND CAPTURE IN THE ETP-TUNA PURSE-SEINE FISHERY?

by

D.A. Pabst, W.A. McLellan, S.A. Rommel, T.K. Rowles,
R.S. Wells, T.M. Williams, A.J. Westgate, M.D. Scott, and E.M. Meagher

ADMINISTRATIVE REPORT LJ-02-01C

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FINAL REPORT

MEASURING SURFACE AND DEEP BODY TEMPERATURES OF DOLPHINS IN THE EASTERN TROPICAL PACIFIC: IS THERMAL STRESS ASSOCIATED WITH CHASE AND CAPTURE IN THE ETP-TUNA PURSE-SEINE FISHERY?

[1]D. A. Pabst, [1]W. A. McLellan, [2]S. A. Rommel, [3]T. K. Rowles, [4]R. S. Wells, [5]T. M. Williams , [6]A.J. Westgate, [7]Michael D. Scott, [1]Erin M. Meagher

1. Biological Sciences and CMS, UNC Wilmington, Wilmington, NC 28403
2. Pathobiology Lab, FMRI, St. Petersburg, FL 33712
3. Office of Protected Resources, NMFS, Silver Spring, MD 20910
4. Chicago Zoological Society, Mote Marine Lab, Sarasota, FL 34236
5. Department of Biology, UC Santa Cruz, Santa Cruz, CA 95064
6. Duke University, Beaufort, NC 28516
7. Inter-American Tropical Tuna Commission, La Jolla, CA 92037

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Explanatory Note

This final report summarizes the objectives and work accomplished by Dr. Ann Pabst and colleagues under P.O. 40ABNF005559, " Measuring surface and deep body temperatures of dolphins in the eastern tropical Pacific: is thermal stress associated with chase and capture in the ETP-tuna purse-seine fishery? ", awarded by NMFS on 8/12/2000. The work was undertaken as part of the research program conducted by the National Marine Fisheries Service as mandated by the International Dolphin Conservation Act (IDCPA).

Although most of the scientists who contributed to the work described herein are not directly affiliated with the National Marine Fisheries Service, the Service has published this report as an Administrative Report in order to contribute to creating an easily-accessible permanent record of IDCPA-related research.

Steve Reilly
Leader, IDCPA Research Program
Southwest Fisheries Science Center
P.O. Box 271
La Jolla, CA 92038

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ABSTRACT

A stated goal of the Workshop on the **Investigation of the Potential Influence of Fishery-Induced Stress on Dolphins in the Eastern Tropical Pacific Ocean** was "to identify physiological and morphological indices that can be practically measured to quantify the effects of stress on dolphins that are chased and captured in the ETP-tuna purse-seine fishery." We hypothesized that dolphins undergoing a prolonged (20 minute-2 hour), high-speed chase in the warm surface waters of the ETP may be experiencing hyperthermic stress. Our goal was to develop an understanding of the relationships between surface body temperature at the dorsal fin, heat-flux across the dorsal fin, and deep body temperatures. An understanding of these relationships may permit an assessment of the thermal status of a wild dolphin at sea by quantifying the temperature profile of its dorsal fin alone. Such measurements could be made remotely by using a high-resolution, infrared, thermographic camera and more directly by using time-depth recorders (TDRs) equipped with temperature and heat-flux sensors. To date, we have accomplished the following goals.

(1) We have extensively field-tested the DTIS 500 infrared camera and determined that although it can function as a near radiometric quality thermal assessment tool under many conditions, it is not a completely reliable quantitative tool. This field-testing was crucial to the success of the thermal component of the ensuing CHESS cruise, as it permitted us to identify the limitations of the DTIS 500 before it was taken to the ETP. It also permitted us to identify the need for a higher magnification capability in the camera system. We were able to identify the FLIR Agema 570 as a highly reliable microbolometer (*i.e.* a radiometric camera) that permitted the CHESS team to collect high-quality, quantitative thermal data in the ETP.

(2) We have designed and deployed thermal trac-pacs that measure skin surface temperature and heat flux of free-swimming, wild bottlenose dolphins (*Tursiops truncatus*). Initial results of these experiments demonstrated that heat flux varies with swimming and surfacing behavior. In the final field experiments, we were able to increase the capacity of the trac-pac by adding a velocity meter to specifically investigate the effect of swimming speed on heat flux and skin temperatures. These experiments permitted us to (1) design and build the thermal datalogging tags that were subsequently deployed in the ETP during the CHESS cruise, and (2) build a comparative data set with which to compare to the ETP records.

(3) We have measured skin surface temperatures and heat flux across the dorsal fin of captive and wild bottlenose dolphins and determined that the fin is a thermally heterogeneous surface and one that changes its thermal properties with exercise. These data permits us to build a comparative data set with which to compare ETP records.

(4) We have measured deep body temperatures in wild bottlenose dolphins to establish range of "normal" temperatures in animals that have undergone a brief chase and capture experience.

In summary, our cumulative data suggest that dolphins must dissipate excess body heat across their thermal windows, and that heat flux values are highest after extended or high-energy exercise bouts. Heat dissipation appears to temporally lag behind peak exercise, and convective heat loss may be an important, though to date, under appreciated mechanism for dumping excess heat.

INTRODUCTION

A stated goal of the Workshop on the **Investigation of the Potential Influence of Fishery-Induced Stress on Dolphins in the Eastern Tropical Pacific Ocean** was "to identify physiological and morphological indices that can be practically measured to quantify the effects of stress on dolphins that are chased and captured in the ETP-tuna purse-seine fishery."

Thermal stress can be associated with chase and capture in terrestrial mammals. Increased core temperatures in terrestrial mammals can cause maladaptive physiological changes and in extreme cases, even death. Hyperthermia may be most severe in pregnant mammals where blood flow to the uterus - required for adequate thermoregulation of the developing fetus - may be compromised by shunting arterial blood flow to either (1) exercising locomotory muscles and/or (2) skin to dump excess heat at the body surface. Decreased blood flow to, and concomitant increased temperatures at the fetus cause detrimental effects including low birth weight, retarded growth, skeletal and neurological developmental anomalies, and ultimately acute fetal stress and death. Based on observations on terrestrial mammals, it is possible that dolphins undergoing a prolonged (20 minute- 2 hour), high-speed chase in the warm surface waters of the ETP may be experiencing hyperthermic stress.

Our goal was to develop an understanding of the relationship between surface body temperature at the dorsal fin, heat-flux across the fin, and deep body temperatures. An understanding of that relationship may permit an assessment of the thermal status of a wild dolphin at sea by quantifying the temperature profile of its dorsal fin alone. Such measurements could be made remotely by using a high-resolution, infrared, thermographic camera and more directly by using time-depth recorders (TDRs) equipped with temperature and heat-flux sensors.

By using the thermographic camera, we could obtain data on thermal stress without handling the dolphins, or even encircling them. This technique would avoid potential biases in the data caused by handling the dolphins. This method would require, however, extensive calibration with internal and external temperatures measured on dolphins held in captivity, wild dolphins held temporarily during captures, and free-ranging dolphins. By using TDRs equipped with thermal sensors, second-by-second data can be obtained from dolphins tagged and released from tuna nets. These detailed data can be collected during normal activities of the dolphin and during subsequent chases and recaptures, if they were to occur.

OBJECTIVE: To investigate the relationship between surface temperatures of bottlenose dolphins, as measured with infrared thermography, and their deep body temperatures, heart and respiration rates, and heat flux patterns across their dorsal fins. These data are required to identify the range of surface temperatures achieved by dolphins under different behavioral states and in different environments. We have examined these relationships under the following two experimental conditions:

(a) warm-water captures of wild bottlenose dolphins in Sarasota, Florida
(b) warm-water exercise regimes of trained dolphins at Dolphin Quest, Hawaii

In our last progress report, we outlined the experiments undertaken in June 2000 in Sarasota, FL, during which wild bottlenose dolphins were captured and briefly restrained as part of a long-term health monitoring program conducted by the Chicago Zoological Society (NMFS Scientific Permit No.522-1569). Experiments for this study were conducted between June 12 and June 23, 2000. These experiments were aimed at getting a suite of thermal data from at least one dolphin per set, as soon as possible after the capture event. Immediately upon restraint, dolphin thermal images and deep core temperatures were taken. To field-test the accuracy of the thermal camera, we placed a known-temperature object in each image frame. After a 10-minute imaging session, we carried out a second thermal experiment. We placed a harness on the dorsal fin that held three heat-flux discs and three thermocouples in place upon the skin surface. Two heat-flux discs were placed near the center of the fin - one directly over and one off a superficial vein - and one at the distal tip. Continuous records of these thermal sensors, along with heart rate and respiration rate, were recorded for 10-15 minute sessions. Our goal was to determine the relationship between respiration rate (a behavior that can be easily and non-invasively measured in the field) and heat-flux rate across the dorsal fin. These experiments, which supplement the thermal dorsal fin tag experiments, are aimed at better understanding whether other non-invasively measured, physiological parameters can be used to assess the thermal status of ETP dolphins. We also deployed six thermal tags. Our observational data techniques have been improved, so that we have virtually continuous respiration records for the tagged animals.

Here we detail the methods and results of those experiments, as well as captive animal experiments undertaken in March 2001, and another field season in Sarasota, FL, during June 2001.

PROGRESS TO DATE

(1) DTIS 500 infrared thermographic camera

Sarasota Bottlenose Dolphin Project, June 2000

To determine the efficacy of the DTIS 500, we analyzed 179 thermal images with a known temperature object in the frame. The temperature of the water's surface, as calculated with the EmergeVision software (IR temp), was also compared to independent water temperature measurements taken during the capture.

The DTIS 500 proved effective as a near-radiometric quality camera under the field conditions we experienced in Sarasota (see attached graphs). The IR temp was highly predictive of the temperature of the solid object (rubber stopper) used as a control during the experiments [IR temp = 0.95 + 0.97(independent bung temp); r^2=0.82] (Figure

1a). Careful analysis of multiple time-series of IR images demonstrated that the camera was highly sensitive to temperature changes that were occurring in our known temperature object during the course of the experiments. That is, the camera accurately tracked temperature fluctuations as they occurred. Rarely, a single frame of thermal data appeared to be corrupted – *i.e.* temperatures would change by 1-2°C in under a minute from the time of the previous image. These frames were always noticeably different than others in a time series and easy to identify as corrupted. The existence of these corrupted files, though, speaks to the importance of taking multiple images when possible.

There was also a significant, though not as strong, positive relationship between IR and independently measured water temperature [IR water temp = 0.4171(independent water temperature) +14.674; r^2=0.62](Figure 1b). The larger scatter of data points for the water temperature measurements may be accounted for in at least two ways. (1) The highly reflective water surface may affect the IR camera's ability to render an accurate temperature. Shadows upon the water surface affected IR temperatures, so we sampled all water surfaces in the frame, and used the mean temperature for comparison. This method, although broadly representative, may not have been the best to accurately represent water temperature. We are currently analyzing shadowed *vs.* unshadowed surfaces to determine if one is more representative of independently measure water temperatures. (2) Our independently measured water temperatures may or may not be representative of the experimental conditions. We used a single water temperature measurement for each set, which was usually taken near the time of the thermal experiment. Water temperature, though, was noticeably variable during many sets, and the experiment itself (*i.e.* placing one dolphin and 6-8 people in close proximity) could have changed local water temperatures. Given the highly predictive relationship between the known-temperature object and the IR camera temperatures, we suspect that a portion of the scatter is due to limitations in our independent water temperature measurements.

Once the efficacy of the DTIS 500 as a radiometric camera was demonstrated, we began analyzing the dorsal fin images. Infrared thermal observations of thirteen bottlenose dolphins, ranging in length from 206-279 cm, were used in this study (Table 1). After the dolphins were captured, they were photographed with the IR camera as soon as possible. The length of time between capture and first infrared thermal image varied, but with the exception of three animals, occurred within 20 minutes. The timeframe for FB 196, FB 155, and FB 33 was 114 minutes, 106 minutes, and 142 minutes, respectively. Because multiple individuals were occasionally captured at a single time, not all animals in a set could be processed immediately. All animals were photographed while being held stationary next to the boat that contained the IR photographer. The distance between the photographer and the animal varied, but was generally within 1-2 meters. The goal was to photograph the animals with their dorsal fins above the surface of the water, however, waves occasionally washed over the fin, creating an almost instantaneous temperature change (Figure 2).

To investigate the pattern of temperature change in the thermal images, nine sites across the dorsal fin were sampled (Figure 3a). Sites 1-3 were the most "proximal" sites, sites 4-6 were "intermediate" and sites 7-9 were the most "distal" sites on the fin (Figure 3b). Sites 1, 4, and 7 were located cranially and along the leading edge of the fin. The mean of the temperatures at these sites were defined as "cranial" (Figure 3c). Sites 3, 6, and 8 were located caudally and along the trailing edge of the fin. The mean of the

temperatures at these sites were defined as "caudal". Site 9 was the "distal tip", the most distal site on the dorsal fin and was compared to cranial and caudal means. Results for each dolphin were examined using spreadsheet software (Excel, Microsoft).

All thirteen animals showed an increase in surface temperature at some position across the dorsal fin over time when the fin remained dry. If portions of the fin remained completely dry throughout the experiment their surface temperatures increased steadily, as shown at sites 4 and 9 of FB 155 (Figure 4). Most sites showed an increase in surface temperatures until they were submerged or doused with water. The largest temperature change occurred in FB 25, whose fin experienced a minimal amount of water disturbance. The initial temperature of site 7 for FB 25, for example, was 30.5°C and the final temperature was 34.6°C (Figure 5).

A majority of dorsal fins exhibited a general warming trend from the proximal to the distal positions (Table 2). In ten of the thirteen animals (77%), the mean for sites 1-3 yielded the coolest temperatures while the mean for sites 7-9 yielded the warmest. The intermediate positions, sites 4-6, yielded mean temperatures that were in between those of the proximal and distal positions. This warming pattern is exemplified by FB 43 (Figure 6a). FB 196, FB 15, and FB 26 did not exhibit this pattern. We know that the temperature of the proximal fin surface of FB 196 was influenced by a recent freeze-brand, which caused an inflammatory response. This response elevated the temperature of sites 1-3 beyond that of the distal sites 7-9 (Figure 6b).

When compared to the cranial and caudal portions of the dorsal fin, the distal tip (site 9) was the warmest part of the fin in nine of the thirteen animals (69%) (Table 3). There was no discernable trend in the cranial and caudal means. However, the caudal temperature profiles were quite variable because the trailing edge of the fin often contained both "cool spots" and "hot spots".

Although efforts were made to keep the dorsal fin above water for the duration of the experiment, each fin was influenced by the effects of water in some manner. When dorsal fins were exposed to water, the temperature in areas within the watermark was cooled by at least 1°C almost instantaneously. This temperature change was readily apparent in the thermal images (see Figure 2). One animal in particular, FB 13, had its dorsal fin submerged twice at two different depths and the temperature change was evident in the thermal image as a three-tiered effect (Figure 7).

Thermal profiles appeared to depend, in part, upon the chase and capture history of the animal. For example, the first attempt at capturing FB 15 was unsuccessful and, subsequently the animal was chased for a second time. After FB 15 was captured, deep (core) body temperatures were recorded and she was initially photographed approximately nineteen minutes after capture. Her deep body temperature averaged 37.1°C and the warmest surface temperature of her fin was 35.0°C. While being photographed with the IR camera, the dorsal fin of FB 15 was affected by water and, as a result, the surface temperature of the dorsal fin decreased (Figure 8). Thermal images were again taken of FB 15 approximately two hours after the initial photos. After being allowed to rest on her own, when her fin was wetted often, the surface temperature of FB 15's dorsal fin decreased. However, as she was being photographed, FB 15's dorsal fin surface temperature began to rise. Although temperatures dipped after the dorsal fin was submerged, they continued to rise throughout the duration of the experiment when the fin was not affected by water.

In contrast, FB 32 was corralled with little to no chase, and his initial deep body temperature averaged 36.6°C. His dorsal fin surface temperatures were rather low, the highest temperature being 32.2°C. However, as the experiment progressed, the surface temperatures of the distal sites of the fin increased (the other sites, especially the proximal sites, were affected by water). Additional thermal images were taken after the animal had just been released from being on the boat, out of the water. Temperatures had increased at all nine of the sites and deep body temperatures decreased (average 36.0°C). The relatively small sample size of animals with both surface and deep body temperatures measured directly after chase and after a subsequent "cool down" period will be addressed in the fieldwork to be carried out in June 2001 in Sarasota, FL.

In summary, a few points are worth noting. (1) Even though the DTIS 500 camera that we used is no longer designed as a veterinary diagnostic tool, it maintains sufficient spatial resolution to effectively image superficial blood vessels on some fins. This feature permits us to follow the types of thermal changes that occur across the fin over time. (2) Dorsal fin skin temperature is variable, dependent both upon anatomical position and time. Most fins warm during the experimental sessions. With time, the entire surface warms, often to the same temperatures as had been observed only directly over the superficial vasculature; the distal tip tends to become the warmest site on the fin. These increased skin temperatures over time might suggest that there is enhanced heat flux across the dorsal fin. As will be discussed below, though, this is not the case - there is decreased heat flux with increased temperature when the fin is in the air.

In summary, the DTIS 500 yielded reliable skin surface temperatures for wild bottlenose dolphins under the field conditions encountered during the June 2000 captures in Sarasota, Florida. Thus, our results suggest that the DTIS 500 can be used effectively as a radiometric camera in the field.

Sarasota Bottlenose Dolphin Project, June 2001

These experiments were repeated in part during June 4-15, 2001. Thermal images were acquired for 18 animals, although only 16 yielded complete thermal data (Tables 4 and 5). Unfortunately, in 2001, the DTIS 500 did not perform as reliably in the field. In contrast to 2000, the gain settings had to be changed repeatedly throughout the experiment to obtain visually acceptable images. Although the thermal imaging software was characterized to us as being fully capable of handling different gain settings, it proved not to be the case. Changes in gain settings often caused dramatic (1-2°C) changes in measured temperatures within an image over short time periods. The magnitude of these changes was also not consistent across the entire field of view. Because gain changes caused unpredictable and inconsistent changes in perceived temperatures, only those images with a constant gain setting were compared. Likewise, unlike 2000, the internal camera temperature also influenced the perceived temperature in the image. Increases in "chopper temperature" (*i.e.* an internal camera temperature at the thermal sensor) caused consistent increases in the perceived temperatures within an image. Thus, only images that shared similar chopper temperatures (defined here as within 0.5°C of each other) were compared.

Despite these limitations, the pattern of temperature changes across dorsal fins could be investigated. As in 2000, all 16 animals showed an increase in surface temperature at some position across the dorsal fin over time when the fin remained dry,

and most sites showed an increase in surface temperatures until they were submerged or doused with water. A majority of dorsal fins also exhibited a general warming trend from the proximal to the distal positions (Table 5). Of the 16 dolphins investigated, 12 (75%) showed higher temperatures at the distal tip than at the most proximal sites.

The problems encountered with the DTIS 500 in 2001 were disturbing, because for the success of the CHESS cruise, we required a completely reliable radiometric camera. The 2001 results suggested that if the DTIS 500 were taken to the ETP, where field conditions would be less controlled than in Sarasota, the camera would not necessarily function in a reliable manner. Above and beyond the concerns about camera performance, we had concerns about the stability of EmergeInteractive, a company that had decreased its support for the camera during our tenure with the product. (In fact, the company ceased its support for the camera altogether in summer 2001). Thus, we began investigating an alternative camera, the FLIR Agema 570. This camera proved a highly reliable microbolometer (*i.e.* a radiometric camera) that subsequently permitted the CHESS team to collect high-quality, quantitative thermal data in the ETP. Our ability to extensively field-test the DTIS 500 infrared camera was crucial to the success of the thermal component of the ensuing CHESS cruise, as it permitted us to identify the limitations of the DTIS 500 before it was taken to the ETP.

(2) Heat flux and skin temperatures across the dorsal fin

Sarasota Bottlenose Dolphin Project, June 2000

Nineteen bottlenose dolphins were fitted with the thermal harness that held three heat-flux discs and three thermocouples in place upon the skin surface. Two heat-flux discs were placed near the center of the fin - one directly over and one off a superficial vein - and one at the distal tip. For the nineteen animals examined, heat flux across the surface of the dorsal fin between the three positions was extremely variable. The mean difference between the two center fin positions was 47.22 W/m2 in air and 36.41 W/m2 in water. The maximum difference measured between the two center fin positions was 129.32 W/m2 for one dolphin - this difference is recorded between two sites on the fin separated by as little as 1 cm. The mean maximum difference between the center of the fin and the distal tip was 58.80 W/m2 in air and 55.36 W/m2 in water. The maximum difference measured across the height of the fin, between a center position and the distal tip, was 168.39 W/m2. Interestingly, these differences in heat flux between the three positions on the fin of a bottlenose dolphin at rest are greater than the differences in heat flow values that have been measured from the thermal windows of dolphins under different behavioral states (*e.g.* diving, exercising, cooling, heating) in prior studies.

For the 13 animals where we were confident that we had placed a heat flux transducer directly over superficial veins in the distal tip and the center of the fin, and definitely off of a vein in the center of the fin, 12 showed heat flux values that were higher over a superficial vein when the fin was submerged. Ten out of these 13 had the highest heat flux values at the distal tip of the fin, while two had heat flux values highest at the center of the fin over a superficial vein. That is, heat flux is higher over the superficial veins when the fin is submerged. These results strongly suggest that surface vasculature influences heat flux across the dorsal fin.

How is temperature and heat flux related to each other at each position on the dorsal fin? The distal tip has the highest average temperature differential between the

skin and the ambient environment followed by the center of the fin on and the center of the fin off of a vein. From this pattern we would expect that in air and water, the distal tip would have the highest heat flux, followed by the center of the fin over a vein and the center of the fin off of a superficial vein. We did observe this pattern of heat flux when the fin is submerged. But this pattern is not observed in air - as temperature differential between air and skin temperature increases, heat flux decreases. For those 13 animals where we were confident that we had placed the heat flux transducers on and away from superficial veins, the heat flux values measured in air show a pattern across the three positions on the fin that did not differ from what would be obtained by chance alone. For these animals, the center off position is equally as likely as the distal tip of the fin to have the highest heat flux values.

We attribute these differences in heat flux patterns between air and water to their different thermal conductivities. Because water has a conductivity 25 times greater than air, heat is dissipated as soon as it is brought to the surface in a superficial vein. Thus, in water, heat flux values parallel changes in temperature differential. Because of the low conductivity of air, heat can't be dissipated from the fin as quickly as it is brought to the surface. The steady increase in skin temperatures over superficial vessels may be caused by a build up of heat brought to the surface from the core, *via* blood, which is not dissipated to the environment.

In conclusion, these experiments show that heat flux values are variable across the surface of the dorsal fin and are positionally dependent when the fin is submerged. The highest heat flux values are measured over superficial veins and heat flux values are usually highest at the distal tip. The variability we recorded in heat flux across the surface of the dorsal fin is as high as that recorded for dolphins under different behavioral conditions. The patterns of heat flux across the dorsal fin vary depending on the ambient environment. In air it appears that although heat is transported to the surface *via* the superficial vasculature, heat is not conducted away. Thus, as heat flux decreases the skin temperature increases. In water, a much more conductive medium than air, heat is transported to the surface of the animal via the superficial vasculature and is quickly dissipated.

Because blood flow is the force driving heat flux across the dorsal fin, were also interested in examining the physiological mechanisms that transport blood to the thermal windows. Thus, during heat flux experiments, we also simultaneously and continuously measured respiratory events and heart rate. Heart Rate was recorded during experimental sessions by a Polar Vantage NV heart rate monitor (Polar Electro, Inc., Woodbury, NY). The monitor was affixed to the dolphin by an elastic belt and transmitted information to a wrist receiver attached directly to the elastic belt. The Polar Vantage NV recorded R-R intervals, thus, effectively measuring each heart beat (maximum storage capacity- 4000 heart beats). After experimental sessions, heart rate information was downloaded from the receiver to a laptop computer for analysis *via* the Polar Vantage Interface system. Heart rate data were cleared from the receiver between each experimental session. The time of each respiratory event, recorded to the nearest second, was recorded on a spreadsheet by a trained observer. Each respiratory event was also recorded by another observer with an electrical trigger, connected to the Fluke Hydra data logger, which placed an event marker in the data file. The two methods of recording respiratory events allowed data to be compared for accuracy.

Heart rate data were collected on 14 of the 19 dolphins, although only 6 records were of sufficient length and quality to analyze. Mean heart rates were calculated from the longest segments of quality data for each animal. These segments were all longer than 4 minutes. Mean heart rate ranged from 72 to 101 beats/min in these six animals. Heart rates were arrhythmic, with periods of tachycardia associated with respiratory events and bradycardia during intervening interbreath intervals. The highest heart rate value occurred within 6 seconds, before or after, a respiratory event an average of 89% (+/- 7.5% SD) of the time (range= 75 - 97%). No clear relationship between a respiratory event and an increase in heat flux across the dorsal fin, in either air or water, was observed

(3) Thermal trac-pac

Data from the previous deployments of the thermal trac-pac have already demonstrated the efficacy of this technology at measuring surface fin temperature and heat-flux. The development the thermal trac-pac has gone through two distinct phases. The first involved the planning and construction of the package, the second entailed deployments on captive and wild bottlenose dolphins. These developmental steps were required to ascertain the efficacy of the trac-pac as a remote thermal sensing tool for wild dolphins in the ETP. We here offer more detailed descriptions of the thermal trac-pac design, and of the results of deployments to date.

The heat flux transducer used in the trac-pac (Vatell episensor B02, Vatell Corp. Christensburg VA) produces a weak signal (0-0.1 mV) at frequencies from dc out to about 1000 Hz. Therefore, we designed a low noise differential dc amplifier with a stable zero and flat response curve that would amplify this signal to between 0-2.5 volts. Each amplifier had a gain of approximately 2500 x. These voltages were then recorded using a modified HOBO 4-channel data logger (Onset Computer Corp. Pocasset, MA). The amplifier also contained a temperature circuit that was connected to an epoxy-encased thermistor (Thermonetics DC95G503W, Edison NJ). Both the HF amplifier and HOBO data logger were encased in Scotchcast #5 electrical resin (3M Austin TX). The second-generation package also contained a HOBO type T thermocouple data logger (Onset Computer Corp, Pocasset, MA). The probe from this device (Omega type T copper-constantan thermocouple wire) was attached to the face of the heat flux disk, which allowed heat flux and temperatures to be collected from the same site on the dorsal fin.

The heat flux disc and skin temperature thermocouple was attached to the dolphin's dorsal fin using a thermo-plastic saddle that had been vacuum molded to fit the contours of the "average" *Tursiops* dorsal fin. The saddle was lined with open cell foam (1/8") and a series of small suction cups. The suction cups adhered to the dorsal fin and held the saddle in place. Two calibrated magnesium linkages at the front of the package corroded in seawater that allowed the saddle to detach from the dolphin. The saddle plastic was constructed from 1/8" modified polyethylene. The plastic had been molded around two syntactic foam (Emerson and Cuming, Canton MA) blocks (approx. 10.5 x 7.0 x 2.5 cm) that had been previously formed into a hydrodynamic shape. These blocks formed two pockets on each side of the saddle and these were partially hollowed out to accommodate the electronic packages. On the right side of the saddle we attached a VHF radio (Holohil, Carp, ON) and Mk-7 time-depth recorder (TDR) (Wildlife Computers,

Woodenville, WA). The VHF transmitters allowed us to radio-track the animals throughout each deployment and recover the packages once they had come off. The TDR allowed us the record the diving behavior and water temperature. On the left side we attached the heat flux disc and skin temperature thermocouple package. The heat flux disk (2.5 x 2.5 cm) was attached to a short spring and pushed up gently against the fin when the saddle was in place. The relative position of the HF disk on each dorsal fin was different because of individual variation in dorsal fin size and shape. Generally they were positioned 7-10 cm behind the leading edge and 6-10 cm from the proximal base of the dorsal fin. A short wire (5 cm) connected the HF disk to the electronics package. Skin temperatures were recorded in two ways. For the first generation, we relied on the thermistor to collect skin temperatures. The thermistor was placed inside one of the small suction-cups so that it rested against the dorsal fin approx. 3 cm caudal to the heat flux disk. In the second generation we incorporated a thermocouple as described above. Water temperature was always collected using a stalked thermistor on the TDR.

Thermistors (both our own and that of the TDR) and thermocouples were calibrated using a temperature controlled water bath Lauda Eco Line high precision water-circulating bath. Each thermal device was placed into the water bath and allowed to equilibrate for a minimum of 5 minutes. Water bath temperatures were varied between 10 and 35 ° C. For the TDRs and thermocouples, water bath temperature was plotted against recorded temperature. For the thermistors water bath temperature was plotted against the recorded voltage and a calibration curve was calculated from these data directly.

These tests demonstrated that we could get accurate and precise heat flow data in the very controlled thermal environment of a water bath. To ensure that the tag could be successfully attached to a dolphin's fin, we live-tested the thermal trac-pac with a captive dolphin at Long Marine Lab, UCSC. The success of this portion of the research project relied heavily upon the unique research opportunities with captive bottlenose dolphins at Long Marine Lab. The iterative tests of the tag that were possible in this captive situation permitted us to make subtle design changes to the heat-flux disk attachment, thus, ensuring the collection of high-quality data in Sarasota.

Sarasota Bottlenose Dolphin Project, June 1999 and 2000

To date we have deployed 12 thermal trac-pacs on wild bottlenose dolphins (7 females and 5 males) in Sarasota, FL. Five individuals were tagged between June 10-15, 1999, and seven individuals were tagged between June 15-23, 2000 (Table 6). If more than one individual was available in a particular set then each fin was tested to find the best fit. Two individuals (FB 117) were tagged in both 1999 and 2000 (Table 6). All dolphins were tracked using small fiberglass outboard driven boats. We tracked the dolphins at distances that ranged between 2-500 m, however we generally kept the boat at least 100 m from the dolphin. Respiration data was collected during each deployment for at least 15 minutes each hour. In addition time stamped positions were recorded using a GPS every 15 minutes and obvious behaviors were also noted at this time. Deployments have ranged between 13 and 480 minutes for a total of 2263 minutes (37.7 hours) (mean = 188.6 ± 158.7 minutes). Ten of the 12 deployments resulted in usable data from all sensors. Two deployments in 2000 had limited or no data (Table 6). Mean heat flux, skin and water temperatures for each deployment are shown in Table 7. The skin temperature data collected during 2000 showed that there was a marked difference between temperatures recorded form the two different skin temperature sensors (Table 7). Generally the thermistor values were lower than those recorded from the thermocouple (see Figures 9-12).

Seven of the 12 deployments terminated as a result of the magnesium linkage breaking. In the other five cases the magnesium linkages were intact suggesting that the package slipped off the fin. In two cases, high-energy activity (breaching, sharking at the surface) was observed just prior to package release suggesting that these dolphins were actively trying to get the packages off. Linkages were calibrated by removing different amounts of magnesium from 24 hours linkages and then soaking these in seawater until they were fully corroded. Since the conditions in these static experiments were different from the conditions on the dolphin it was difficult to fine-tune the release times to more than ± 3 hours. Longer deployments could be more accurately calibrated than shorter ones.

Examples of individual heat flux and temperature records are shown in Figures 9-12. A portion of the heat flux record from FB 119 is shown in Figure 13 to offer a more fine-scale temporal view of the relationship between heat flux and surfacing behavior. This record shows the patterns in heat flux readings taken over three consecutive dives. Heat flux readings peak (270-290 W/m2) during the middle of each of the dives. Heat flux starts to fall off just before the ventilation sequence begins and reaches a minimum (245-250 W/m2) at the beginning of the next dive. This pattern was repeated through the deployment. This pattern was also seen in other deployments (e.g. FB 15, Fig. 11).

Mean heat flux and temperature variation among tagged dolphins (Table 7). Since each dorsal fin was a different size, the actual placement of the HF disk relative to the rest of the fin, and therefore, underlying vasculature, varied. There may be individual variation in the absolute heat flux values that could depend upon factors such as body size, reproductive condition and physiological state. Other sources of variation can be attributed to how the actual package fit on the dorsal fin and the length of deployment.

This pattern of heat flux was not expected, because static measurements of heat flux on captive dolphins have suggested that the heat flux increases at the surface after a dive to depth (Noren *et al.* 1999, Williams *et al.* 1999). We offer the following

alternative hypotheses for the pattern observed in freely swimming wild dolphins:

(1) The decrease in heat flux at the surface could be due to the lower heat conductivity of air vs. water. This hypothesis is not well supported since heat flux readings begin to decline before the dolphin breaks the surface and take over a minute to reach maximum value after the dive begins. The Vatell heat flux discs are extremely sensitive and time-responsive, so we would expect the disc to respond more quickly if the major influence on heat flux was the conductivity of the fluid media.

(2) Decrease in heat flux at the surface could be related to real physiological changes in the animal, such as heart rate. Interestingly, heat flux appears to be decreasing at the surface with a respiratory event, which is temporally correlated to tachycardia, and increasing at mid-dive, a time period usually associated with bradycardia. This pattern is clearly against the "dogma". Tachycardia may cause increases in heat flux in wild swimming dolphins, but perhaps there is a significant time delay between that event and a measurable effect at a distal appendage. There was no measurable temporal relationship between tachycardia and increases of heat flux at the dorsal fin in the stationary experiments (see above). The relationship between cardiovascular events and heat flux patterns is clearly one that requires further investigation.

(3) Decreases in heat flux at the surface could reflect decreases in swimming speed at the surfacing event. The effects of convective fluid forces on heat flux patterns have never been investigated in a swimming cetacean. This year, we will be using the MK8 "speedo" TDR to the thermal trac-pac. The use of this sensor will enable us to directly relate swim speed (and, thus, relative convective forces) to heat flux patterns

(4) The effects we observed may, of course, be an artifact of the thermal sensing system. Because of the highly calibrated time series of data, and the improvements in our tracking made in 2000, we believe it unlikely that the patterns we are observing are due to measurement artifacts.

In summary, the thermal trac-pac worked well in all tank trials and follow-up field deployments. We were able to collect heat flux and temperature data from 10 of 12 deployments. The addition of the Mk 8 "speedo" TDR will enable us to directly correlate swimming activity to heat flux patterns. We find no reason to expect that the present system would not perform well on ETP dolphins.

Sarasota Bottlenose Dolphin Project, June 2001

Several modifications were made to the heat flux recorder during the winter of 2000. These changes included the incorporation of a velocity sensor into the package and improvement of the waterproof coating on the heat flux transducer. Both these modifications were made in anticipation of the CHESS cruise, which was planned for summer 2001. The velocity sensor was a necessary addition since it would allow us to look for the influence of chase on the heat flux record and the improved coating was critical since ETP dolphins were potentially diving to depths that would have compromised our previously used, waterproofing system.

The addition of the velocity sensor allowed us to investigate the interaction between diving, speed and heat flux in Sarasota dolphins. Previous deployments on Sarasota dolphins suggested that heat flux readings peaked during the middle of dives, decreased just prior to surfacing and reached a minimum at the beginning of the next dive. These patterns suggested that heat flux was increasing during presumed diving bradycardia and decreasing during respiratory tachycardia. We hypothesized that the increased heat flux we observed during a dive may be related to a time lag between respiratory tachycardia and peripheral vasodilation at the fin and/or increased speed and, thus, convective heat loss at depth. We proposed to test the latter hypothesis directly by incorporating velocity sensors into the package.

Eight deployments of the heat flux recorder were made during 2001 captures in Sarasota Fl. In total over 16 hours of data were collected (Tables 6 and 7). Unfortunately, several of these deployments collected no or only partial data owing to problems with the retention of tags, TDR software, and downloading malfunctions. We were able to deploy the new heat flux recorder with the velocity sensor (Mk 8 TDR) four times. Of these deployments, only one (FB 63) collected a significant data record. This deployment was 8 hours long during which time the dolphin was tracked out into the Gulf of Mexico. The complete data records (heat flux, skin temperature, water temperature, velocity and depth) for this deployment are shown in Figures 14-17. In order to examine the influence of velocity on the heat flux records we looked at several portions of the track in detail (see Figures 18 and 19). It was evident from this analysis that for this individual, FB63, there were no obvious relationships between diving, velocity and heat flux. That is, we did not observe the patterns between heat flux and surfacing that were evident in most of the previous deployments. In contrast, the 11-minute record we obtained from FB113 (Figure 20) demonstrated the heat flux/surfacing pattern that we had observed in dolphins in prior years. Unfortunately the record for FB 113 is too short to make any definitive conclusions. Without more data it is difficult to determine whether the lack of association we observed between heat flux and surfacing in FB63 was the result of modifications that we made to the tag or a reflection of the physiological differences in this animal. Because we used the same trac-pac on FB 113, and saw a pattern similar to that observed in other animals, it is possible that FB 63 simply displayed a different pattern than other dolphins. It is still possible that the additional waterproofing we added to the heat flux transducer slowed down the response time enough that it masked some of the more fine scale events that we were able to record. We plan to carry out bench testing of both coatings used on the heat flux discs, and to deploy the heat flux/velocity recorder again in 2002. Additional data collected from multiple animals will allow us to examine the relationship between heat flux, diving and velocity in more detail.

(4) Captive animal experiments

From March 4-15, 2001, we traveled to Oahu, Hawaii to carry out thermal experiments with four captive dolphins at Dolphin Quest. These experiments were designed to measure skin surface temperature and heat flux before and after extreme exercise regimes. Extreme exercise regimes included full leaps and breaches, tailwalks, and extended point A to B swimming regimes. Skin surface temperatures were measured with the DTIS 500 infrared thermal camera, an Omega type T thermocouple, and a

Thermonetics heat flux and thermal sensor. Heat flux was measured with both Vatell and Thermonetics heat flux sensors.

We will focus this discussion of preliminary results of heat flux measurements across the dorsal fin to the female dolphin, Hiiaka, because she achieved the highest level of exercise. Five experiments were conducted with Hiiaka, however the third experiment was aborted before any exercise activities began due to interference from a male dolphin, Hoku. Hiiaka underwent periods of exercise lasting from approximately 9 to 23 minutes and her activity level during these bouts of exercise ranged from mild (3 jumps and 1 tailwalk over 20 minutes) to high (12.5 jumps and 3 tailwalks over 19 minutes). Heat flux measurements were taken before and after exercise from two, three, or six positions on the dorsal fin.

In Hiiaka's first experiment, heat flux measurements were taken simultaneously at two positions in the center of the dorsal fin; one position directly over a superficial vein and one position avoiding a superficial vein. Infrared thermography, as well as visual inspection and palpation of the fin were used to determine the position of superficial veins. The infrared camera was also used to assess "hot spots" on the dorsal fin. In Hiiaka's second experiment, heat flux measurements were taken simultaneously at three positions on the dorsal fin; one position directly over a superficial vein, one position avoiding a superficial vein and one position on the trailing edge of the dorsal fin (a hot spot located by the infrared camera). In Hiiaka's fourth and fifth experiments, heat flux measurements were taken from six locations on the dorsal fin. Heat flux measurements were taken simultaneously at three positions at the center of the dorsal fin; one position directly over a superficial vein, one position avoiding a superficial vein and one position on the trailing edge. Heat flux measurements were then collected simultaneously from three positions along the height of the dorsal fin; one position at the base of the fin, one at the center, and one at the distal tip of the fin.

The results of these experiments can be seen in Figures 21-24. After mild exercise, there is little change in heat flux across the dorsal fin, and skin surface temperatures have decreased (Figure 21). These results are in concordance with preliminary analysis of infrared thermal images. During the second experiment, Hiiaka underwent a more strenuous exercise regime, and both heat flux and skin temperature increased at the trailing edge (Figure 22). As in experiment 1, though, there was little change in heat flux between the two center positions. Experiments 4 and 5 were also medium to heavy exercise period, and after these trials, heat flux values were substantially higher than they were pre-exercise. These results suggest that (1) the dorsal fin is a dynamic thermal surface with regionally specific heat flows and (2) that heavy exercise increases the amount of heat dissipated across the dorsal fin. Another interesting feature of these experiments is that the highest heat flux measurements were not made immediately after exercise, but after a 4-6 minute lag period. This result suggests that there may be a time lag between a dolphin's build up of internal heat, and its ability to dissipate it across its thermal windows.

The experiments at Dolphin Quest, Oahu, also permitted us to add to a comparative heat flux data set that Dr. Terrie Williams has been gathering. The previous tests by Terrie, as well as the collaborative effort at Dolphin Quest, Oahu, were designed to evaluate the effects of activity on thermoregulation in bottlenose dolphins acclimated to warm water. Two groups of animals were tested, two adult male dolphins (*Tursiops*

truncatus) from the US Navy Marine Mammal Program (Oahu, HI), and 2 adult female dolphins and an immature male from Dolphin Quest, Oahu. All animals were housed in salt water enclosures exposed to the ocean and ambient temperatures. Average water temperatures during the experiments ranged from 23.2 - 25.9 °C. Five levels of activity were examined, 1) rest, 2) free swimming for 7 min at 2.7 m/s termed cruising, 3) stop-and-go activity for 20-30 min, 4) sprint swimming at 4.1 m/s for 2 min, and 5) wave-riding for 10 min behind a moving boat at 4.5 m/s. Heat flow and skin temperature were measured using a hand held heat flux transducer with embedded thermocouple (Thermonetics Corp., San Diego) placed on the animal following each test period. Measurement sites included thermal windows (dorsal fin, flukes) and insulated areas (mid flank). Except for the stop and go trials, core temperatures were also recorded with a flexible thermocouple probe inserted into the rectum at the level of the counter current heat exchanger (Pabst *et al.*, 1995).

Preliminary results indicate that heat transfer in warm acclimated dolphins depends on anatomical site and type of activity (Figure 25). Few changes in heat flow were noted for the flank regardless of activity level. In comparison, the highest and most variable areas of heat flow were for the thermal windows. Heat flows from the dorsal fin following cruising and stop-and-go activities were the highest recorded in this study reaching 340.0 W/m^2. Sprinting also resulted in an increase in heat flow from the dorsal fin that was nearly 60 W/m^2 above resting levels. Interestingly, wave-riding resulted in few changes in heat flow from any of the sites monitored, and indicates the influence of forced convective cooling for dolphins. Although the wave-riding dolphins were moving at sprint speeds, energetic effort was reduced (Williams *et al.*, 1992) and water flow past the thermal windows was facilitated. This finding explains in part the exceptionally high levels of heat flow for cruising at moderate speeds and stop-and-go activities (Figure 25 A and B).

Measurements of core body temperatures within and outside of the counter current heat exchanger indicate the importance of this convective heat loss mechanism for thermal balance during activity and recovery. For example, cruising at 2.7 m/s for 7 min resulted in a 0.5°C increase in core temperature and a 0.5°C decrease in counter-current temperature. The changes remained stable for 10 min following exercise and then began to return to resting levels over the following 15 min period. Full recovery took nearly 30 min although this was considered a moderate, short duration activity level.

In general, our preliminary results show that convective cooling is a critical feature of dolphin thermoregulation. Stop-and-go or prolonged cruising activities appear to be the most challenging in terms of heat dissipation for dolphins in warm water. Recovery periods even for short duration events may take 30 min or more and raises questions regarding the thermal stability of dolphins involved in ETP fisheries.

SUMMARY

In summary, our cumulative data suggest that dolphins must dissipate excess body heat across their thermal windows, and that heat flux values are highest after extended or high-energy exercise bouts. Heat dissipation appears to temporally lag behind peak exercise, and convective heat loss may be an important, though to date, under appreciated mechanism for dumping excess heat. This research project has accomplished the following goals.

(1) Field-tested infrared thermal camera system.

We have extensively field-tested the DTIS 500 infrared camera and determined that although it can function as a near radiometric quality thermal assessment tool under many conditions, it is not a completely reliable, quantitative tool. This field-testing was crucial to the success of the thermal component of the ensuing CHESS cruise, as it permitted us to identify the limitations of the DTIS 500 before it was taken to the ETP. It also permitted us to identify the need for a higher magnification capability in the camera system. We were able to identify the FLIR Agema 570 as a highly reliable microbolometer (*i.e.* a radiometric camera) that permitted the CHESS team to collect high-quality, quantitative thermal data in the ETP.

(2) Designed and deployed thermal trac-pacs that measure skin surface temperature and heat flux of free-swimming, wild bottlenose dolphins (*Tursiops truncatus*).

Initial results of these experiments demonstrated that heat flux varies with swimming and surfacing behavior. In the final field experiments, we were able to increase the capacity of the trac-pac by adding a velocity meter to specifically investigate the effect of swimming speed on heat flux and skin temperatures. These experiments permitted us to (1) design and build the thermal datalogging tags that were subsequently deployed in the ETP during the CHESS cruise, and (2) build a comparative data set with which to compare ETP records.

(3) Measured bottlenose dolphin dorsal fin surface temperatures and heat flux both at rest and after extended exercise.

We have measured skin surface temperatures and heat flux across the dorsal fin of captive and wild bottlenose dolphins and determined that the fin is a thermally heterogeneous surface and one that changes its thermal properties with exercise. These data permits us to build a comparative data set with which to compare ETP records.

(4) Measured deep body temperatures in wild bottlenose dolphins to establish range of "normal" temperatures in animals that have undergone a brief chase and capture experience to provide comparison to data collected during CHESS cruise.

PRODUCTS

(1) Testing the efficacy of DTIS 500 as a near radiometric infrared camera that can be used to assess the surface temperatures of dolphins under the field conditions likely to be encountered in the ETP. Although the camera could be used to make quantitative comparisons across individuals under certain circumstances, it was rendered a more qualitative thermal tool when comparing images under different environmental conditions, and its quality degraded over time. Our recommendation was to seek out a more reliable, field ready infrared thermal camera system.

(2) Identification of the FLIR Systems AGEMA 570, as a field-ready microbolometer capable of true quantitative comparison of temperatures across all environmental conditions.

(3) Development of thermal trac-pac, which can be used to assess the thermal status of free-swimming wild dolphins.

(4) Enhancement of the thermal trac-pac design to include velocity recorder, which was required for ETP CHESS cruise.

(5) Presentation at the 13th Biennial of the Society for Marine Mammalogy, Maui, November 28-December 3, 1999: "An instrument to record heat flux and surface temperatures from free-swimming dolphins." Westgate, A.J., Pabst, D.A., McLellan, W.A., Williams, T., Wells, R.S., and M.D. Scott.

(6) Presentation at the Society for Integrative and Comparative Biology Meetings, Chicago, January 3-8, 2001: "Respiration, heart rate and heat flux across the dorsal fin in wild bottlenose dolphins, *Tursiops truncatus*." Meagher, E.M., McLellan, W.A., Westgate, A.J., and R.S. Wells.

(7) Presentation at the First Annual Southeast and Mid-Atlantic Marine Mammal Symposium, Mar. 30-Apr. 1, 2001. Beaufort, North Carolina: "Vascular patterns and heat flux across the dorsal fin in wild bottlenose dolphins, *Tursiops truncatus*" Meagher, E.M., Pabst, D. A., McLellan, W. A., Westgate, A., and R. S. Wells.

(8) **Master's thesis**: Ms. Erin M. Meagher. 2001. Respiration, heart rate and heat flux across the dorsal fin in bottlenose dolphins, *Tursiops truncatus*. UNCW.

(9) **Honors Undergraduate thesis**: Ms. Tara Marie Harradine. 2001. Using infrared thermography as a tool for determining the thermal status of bottlenose dolphins, *Tursiops truncatus*. UNCW.

(10) Presentation at the 14th Biennial of the Society for Marine Mammalogy, Vancouver, November 28-December 3, 2001: "Some like it hot: Measuring heat flux and temperature from wild bottlenose dolphins." Westgate, A.J., Pabst, D.A., McLellan, W.A., Meagher, E.M., Wells, R.S., Scott, M.D., Williams, T.M., Rommel, S.A., and T. K. Rowles.

(11) Presentation at the 14th Biennial of the Society for Marine Mammalogy, Vancouver, November 28-December 3, 2001: "The use of infrared thermography to assess thermal function of the bottlenose dolphin (*Tursiops truncatus*) dorsal fin." Pabst, D.A., Harradine, T.M., McLellan, W.A., Scott, M.D., Wells, R.S., Williams, T.M., Westgate, A.J., Meagher, E.M., Rommel, S.A., Hurley, W. and M.M. Barbieri.

(12) Presentation at the 14th Biennial of the Society for Marine Mammalogy, Vancouver, November 28-December 3, 2001: "Vascular patterns and heat flux across the dorsal fin in wild bottlenose dolphins, *Tursiops truncatus*." Meagher, E., Pabst, D.A., McLellan, W., Westgate, A., Wells, R.

(13) **Honors Undergraduate thesis**: Ms. Michelle M. Barbieri. 2002. Using infrared thermography as a tool for determining the effect of exercise on the function of the dorsal fin of bottlenose dolphins, *Tursiops truncatus*. UNCW.

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Table 1. Bottlenose dolphins (*Tursiops truncatus*) used in study. Data collected during biomonitoring study in Sarasota Bay, Florida. The * indicates the age of the animal is unknown.

Animal ID #	Date	Air Temp (°C)	Water Temp (°C)	Sex	Age	Total Length (cm)
FB 196	6/12/00	30.6	N/E	M	2	206
FB 25	6/13/00	31.7	29.8	F	22	270
FB 178	6/15/00	32.2	27.8	M	5	223
FB 174	6/15/00	32.2	29.6	M	*	254
FB 32	6/16/00	30.7	29.6	M	20	253
FB 109	6/16/00	31.9	31.9	F	5	228
FB 15	6/20/00	31.1	29.8	F	50	N/E
FB 155	6/20/00	31.1	30.5	F	10	239
FB 13	6/22/00	30.9	31.4	F	41	245
FB 48	6/23/00	30.8	30.8	M	41	252
FB 33	6/23/00	30.8	30.5	F	18	252
FB 26	6/23/00	30.2	29.4	M	43	279
FB 43	6/23/00	30.2	30.6	F	34	257

Table 2. Proximal, intermediate, and distal area means of the dorsal fin. The * indicates animals that did not exhibit the distal > intermediate > proximal pattern. The [a] indicates FB 196 with freeze-brand located in the proximal portion of the fin.

Animal ID #	Date	Proximal Mean (°C)	Intermediate Mean (°C)	Distal Mean (°C)
FB 196*[a]	6/12/00	33.79	32.2	33.16
FB 25	6/13/00	31.03	32.59	32.92
FB 178	6/15/00	30.06	31.14	31.28
FB 174	6/15/00	29.09	31.08	31.93
FB 32	6/16/00	29.60	30.98	32.19
FB 109	6/16/00	31.17	31.98	32.13
FB 15*	6/20/00	31.87	32.78	32.73
FB 155	6/20/00	32.50	33.42	33.83
FB 13	6/22/00	30.86	31.31	33.18
FB 48	6/23/00	29.99	30.28	30.75
FB 33	6/23/00	31.67	33.71	34.07
FB 26*	6/23/00	30.28	30.08	30.31
FB 43	6/23/00	30.20	32.62	33.05

Table 3. Cranial, caudal, and distal tip means of the dorsal fin. The * indicates animals that exhibit warmer cranial means as compared to caudal means.

Animal ID #	Date	Cranial Mean (°C)	Caudal Mean (°C)	Distal Tip Mean (°C)
FB 196	6/12/00	33.00	33.15	33.03
FB 25*	6/13/00	31.87	31.81	33.92
FB 178	6/15/00	30.02	31.70	31.32
FB 174*	6/15/00	30.91	28.49	31.89
FB 32	6/16/00	30.51	31.06	32.97
FB 109*	6/16/00	32.48	30.74	32.16
FB 15	6/20/00	31.93	33.24	32.74
FB 155*	6/20/00	33.58	32.47	35.38
FB 13	6/22/00	31.24	31.8	34.1
FB 48*	6/23/00	30.46	29.93	31.06
FB 33	6/23/00	32.71	33.40	34.32
FB 26*	6/23/00	28.35	27.73	28.71
FB 43*	6/23/00	32.21	31.32	33.21

Table 4. Bottlenose dolphins (*Tursiops truncatus*) used in infrared thermal study in Sarasota, FL, during June 2001.

ID#	Date	Air Temp	Measured Water Temp	IR Water Temp	Sex	Age (years)	Total Length (cm)
FB 106	04-Jun-01	27.8	32.1	29.9	M	20	244
FB 5	05-Jun-01	NE	30.2	28.7	F	38	242
FB 92	07-Jun-01	31.8	29.3	25.2	M	13	236
FB 138	11-Jun-01	30.7	30.7	29.0	M	9	250
FB 163	15-Jun-01	32.3	32.0	30.0	F	30	255
FB 6	04-Jun-01	NE	31.8	30.1	M	17	261
FB 33	05-Jun-01	NE	30.2	29.0	F	19	252
FB 84	05-Jun-01	31.0	30.4	28.4	F	43	247
FB 118	07-Jun-01	29.1	30.4	28.8	M	9	236
FB 175	07-Jun-01	32.9	30.8	28.7	F	10	240
FB 109	07-Jun-01	NE	31.1	29.0	F	6	234
FB 63	11-Jun-01	30.1	30.8	29.3	F	47	259
FB 119	12-Jun-01	NE	29.7	29.1	F	10	241
FB125	12-Jun-01	NE	30.1	28.9	F	3	228
FB 131	12-Jun-01	NE	NE	29.0	F	13	239
FB 214	12-Jun-01	NE	31.8	30.0	M	2	194
FB 66	14-Jun-01	NE	30.9	30.4	M	25	270
FB 90	08-Jun-01	NE	31.8	28.8	F	31	258

Table 5. Summary of animals with reliable thermal images from June 2001: gain is constant and chopper temperature varies less than 0.5 degrees. Proximal, intermediate, and distal area means of the dorsal fin are listed.

ID#	Date	Proximal Mean	Intermediate Mean	Distal Mean
FB 106	04-Jun-01	32.9	33.6	34.5
FB 5	05-Jun-01	INC	INC	INC
FB 92	07-Jun-01	26.6	26.5	26.4
FB 138	11-Jun-01	29.8	30.4	31.2
FB 163	15-Jun-01	INC	INC	INC
FB 6	04-Jun-01	31.9	32.1	33.2
FB 33	05-Jun-01	32.2	32.5	32.3
FB 84	05-Jun-01	29	29	29.7
FB 118	07-Jun-01	30.5	30.8	31.1
FB 175	07-Jun-01	30.1	30.2	30.4
FB 109	07-Jun-01	29.5	29.6	29.5
FB 63	11-Jun-01	29.9	30	31.2
FB 119	12-Jun-01	29.4	29.7	30.4
FB125	12-Jun-01	29.6	29.7	31.2
FB 131	12-Jun-01	29.7	30.1	30.6
FB 214	12-Jun-01	31.6	32.1	30.6
FB 66*	14-Jun-01	32	32.9	33.3
FB 90*	08-Jun-01	32.7	32.9	32.7

*Means calculated are for one thermal image ONLY (there was only one complete record at sites 1-9 on the fin)

INC: Incomplete record; no set of temperature data with measurements at all 9 sites.

Table 6. Heat flux tag deployments on bottlenose dolphins 1999-2001.

Animal ID	Date	Sex	Length (cm)	Reproductive Status	Duration of Deployment	Comments
1999						
F157	10-Jun-99	Female	190	mature	0 h 30 m	Heat flux and temp data
F117	10-Jun-99	Female	141	?	4 h 9 m	Heat flux and temp data
FB 33	11-Jun-99	Female	177	mature	0 h 37 m	Heat flux and temp data
F192	14-Jun-99	Male	277	mature	7 h 25 m	Heat flux and temp data
PRNIC	15-Jun-99	Male	278	mature	1 h 20 m	Heat flux and temp data
2000						
FB 58	15-Jun-00	Male	270	?	5 h 33 m	Pack malfunction; temp data only
FB117	16-Jun-00	Female	239	?	1 h 26 m	Pack malfunction; no data
FB14	20-Jun-00	Male	267	mature	2 h 47 m	Heat flux and temp data
FB15	21-Jun-00	Female	?	mature	3 h 00 m	Heat flux and temp data
FB119	22-Jun-00	Female	237	?	7 h 59 m	Heat flux and temp data
FB33	23-Jun 00	Female	252	mature	0 h 13 m	Heat flux and temp data
FB48	23-Jun-00	Male	252	mature	2h 44m	Heat flux and temp data
2001						
FB06	04-Jun-01	Male	261	mature	0 h 1 m	Pack off immediately
FB84	05-Jun-01	Female	247	mature	2 h 48 m	Heat flux and temp data No depth record
FB118	07-Jun-01	Male	236	Immature	0 h 5 m	Heat flux and temp data

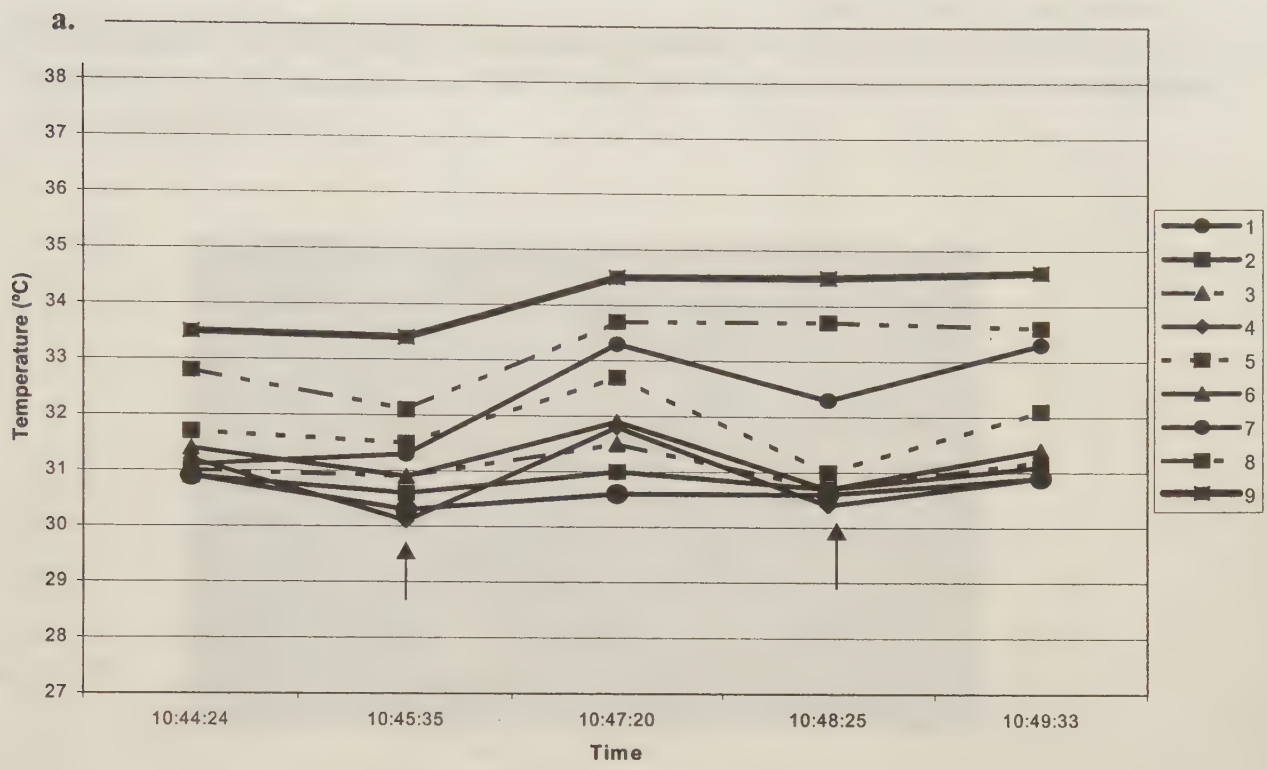
FB175	07-Jun-01	Female	240	?	1 h 56 m	Heat flux/water temp only
FB182	08-Jun-01	Male	257	?	1 h 16 m	Downloading malfunction; Velocity/depth record only
FB113	08-Jun-01	Female	217	Immature	0 h 11 m	Heat flux and temp data Velocity/depth record
FB63	11-Jun-01	Female	259	Mature	7 h 52 m	Heat flux and temp data; Velocity/ depth record
FB09	12-Jun-01	Female	244	Mature	0 h 1 m	Pack off immediately

Table 7. Mean values from heat flux and temperature sensors from 1999-2001.

Animal ID	Date	Sex	Mean Heat flux (W/m2 ± SD)	Mean Thermistor Skin Temperature (°C ± SD)	Mean Thermocouple Skin Temperature (°C)	Mean Water Temperature (°C ± SD)
1999						
F157	10-Jun-99	Female	125.9 ± 54.2	29.4 ± 0.3	na	28.9 ± 0.7
F117	10-Jun-99	Female	322.8 ± 78.9	35.0 ±1.1	na	29.1 ± 0.2
FB 33	11-Jun-99	Female	33.9 ± 52.7	33.7 ± 0.7	na	30.1± 0.5
F192	14-Jun-99	Male	79.5 ± 24.8	30.4 ± 0.3	na	31.1 ± 0.3
PRNIC	15-Jun-99	Male	290.0 ± 140.4	31.6 ± 0.4	na	30.8 ± 0.5
2000						
FB 58	15-Jun-00	Male	no data	29.6 ± 0.3	30.4 ± 0.4	29.5 ± 0.3
FB117	16-Jun-00	Female	no data	no data	no data	no data
FB14	20-Jun-00	Male	204.7 ± 152.1	31.0 ± 0.3	33.5 ± 0.5	30.7 ± 0.3
FB15	21-Jun-00	Female	162.0 ± 46.0	31.1 ± 0.3	34.1 ± 0.3	30.5 ± 0.3
FB 119	22-Jun-00	Female	237.8 ± 38.4	31.7 ± 0.4	34.5 ± 0.6	31.2 ± 0.3
FB 33	23-Jun 00	Female	46.0 ± 22.6	31.0 ± 0.3	33.2 ± 0.4	30.7 ± 0.2
FB 48	23-Jun-00	Male	1.0 ± 33.9	32.2 ± 0.7	35.0 ± 0.8	31.9 ± 0.8
2001						
FB06	04-Jun-01	Male	no data	na	no data	no data
FB84	05-Jun-01	Female	83.1 ± 16.7	na	31.3 ± 0.7	30.8 ± 0.7

FB118	07-Jun-01	Male	96.3 ± 26.8	na	31.9 ± 0.6	31.7 ± 1.3
FB175	07-Jun-01	Female	141.1 ± 52.8	na	malfunction	31.0 ± 0.8
FB182	08-Jun-01	Male	no data	na	no data	29.6 ± 0.1
FB113	08-Jun-01	Female	65.7 ± 31.8	na	33.3 ± 0.8	31.5± 0.3
FB63	11-Jun-01	Female	76.8 ± 31.7	na	32.6 ± 0.6	31.3 ± 0.7
FB09	12-Jun-01	Female	no data	na	no data	no data

Figure 1. Comparisons of infrared (IR) *vs.* independently measured temperatures.
a. Independently measured stopper temperature *vs.* IR stopper temperature.
b. Independently measured water temperature *vs.* IR water temperature.



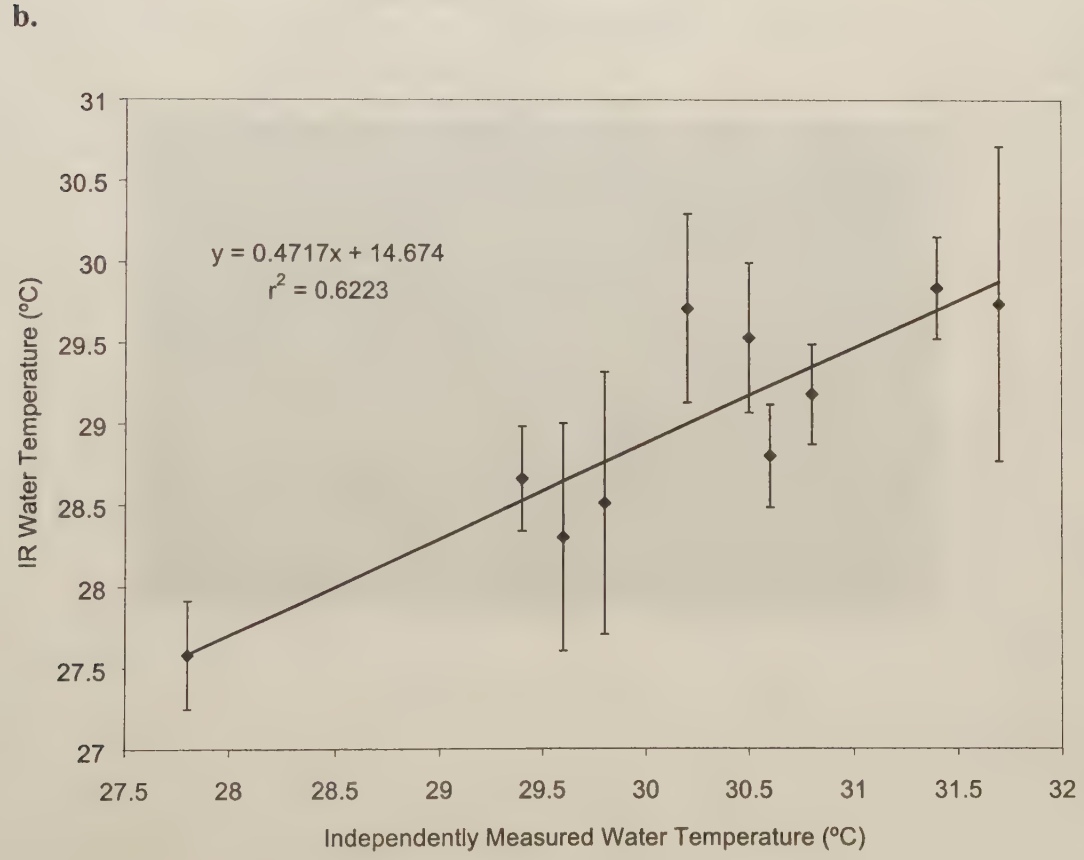
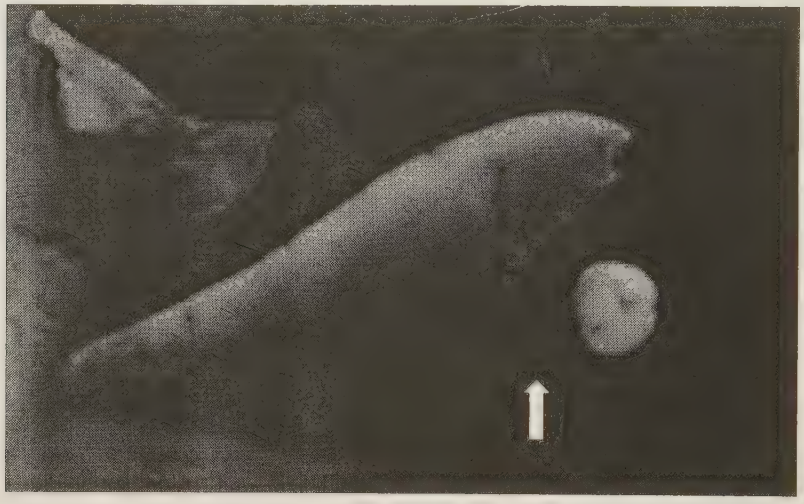


Figure 2. Thermal images of FB 174. In this image, as in all others, the lighter the surface, the warmer its temperature.

a. Thermal image taken before dorsal fin partly submerged in water. White arrow indicates the rubber stopper used in study.
b. Thermal image taken after dorsal fin partly submerged in water. Note the decrease in the temperature of the fin surface that was just submerged.

a.



b.

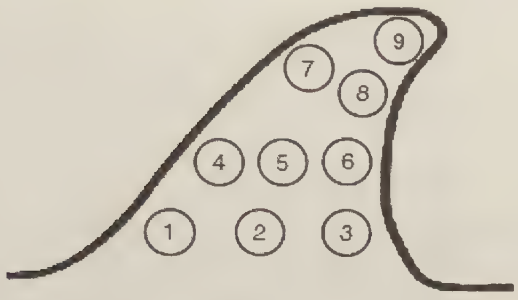
Figure 3. Schematic representation of measurement sites used to assess thermal images.

a. The nine sites that were sampled across the dorsal fin.

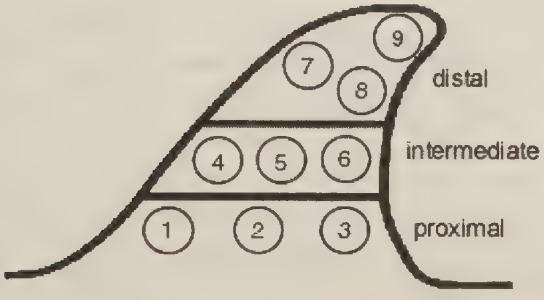
b. The proximal, intermediate, and distal areas and the sites within each that were sampled. A measurement reported for a given region represents the mean for the three sites contained therein.

c. Delineation of the areas that were sampled as part of the cranial, caudal, and distal potions of the dorsal fin. A measurement reported for a given region represents the mean for the three sites contained therein.

a.



b.



c.

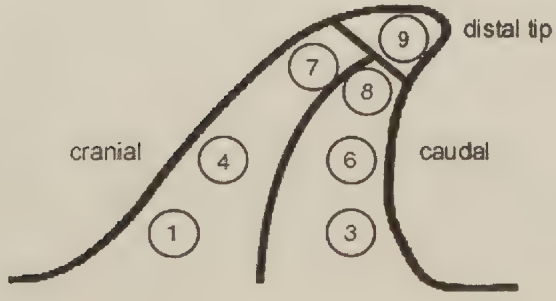


Figure 4. Thermal profile of sites 1-9 for FB 155. Arrows indicate partial/complete submergence in water. Note how temperature increases at sites 4 and 9, which remain dry throughout most of the experiment.

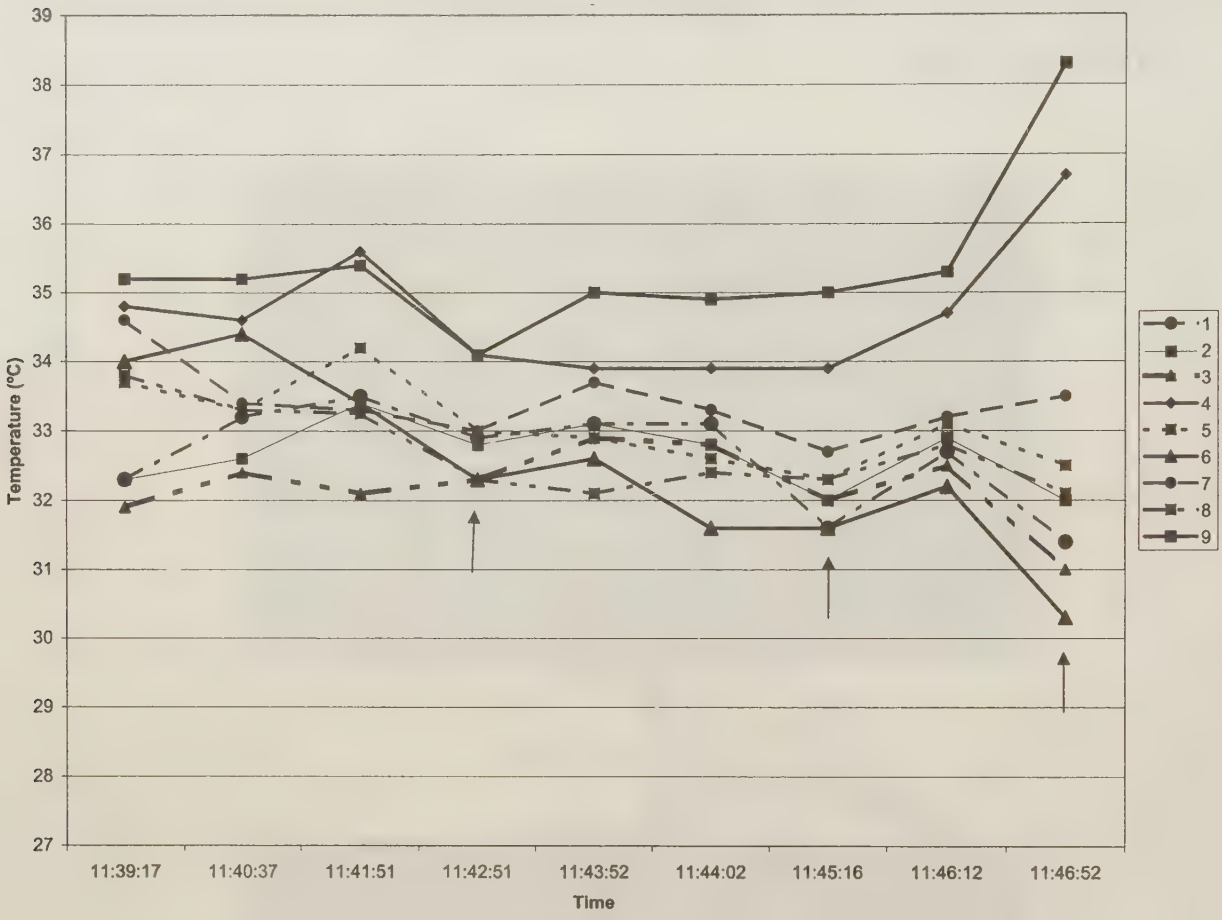


Figure 5. Thermal profile of sites 1-9 for FB 25.

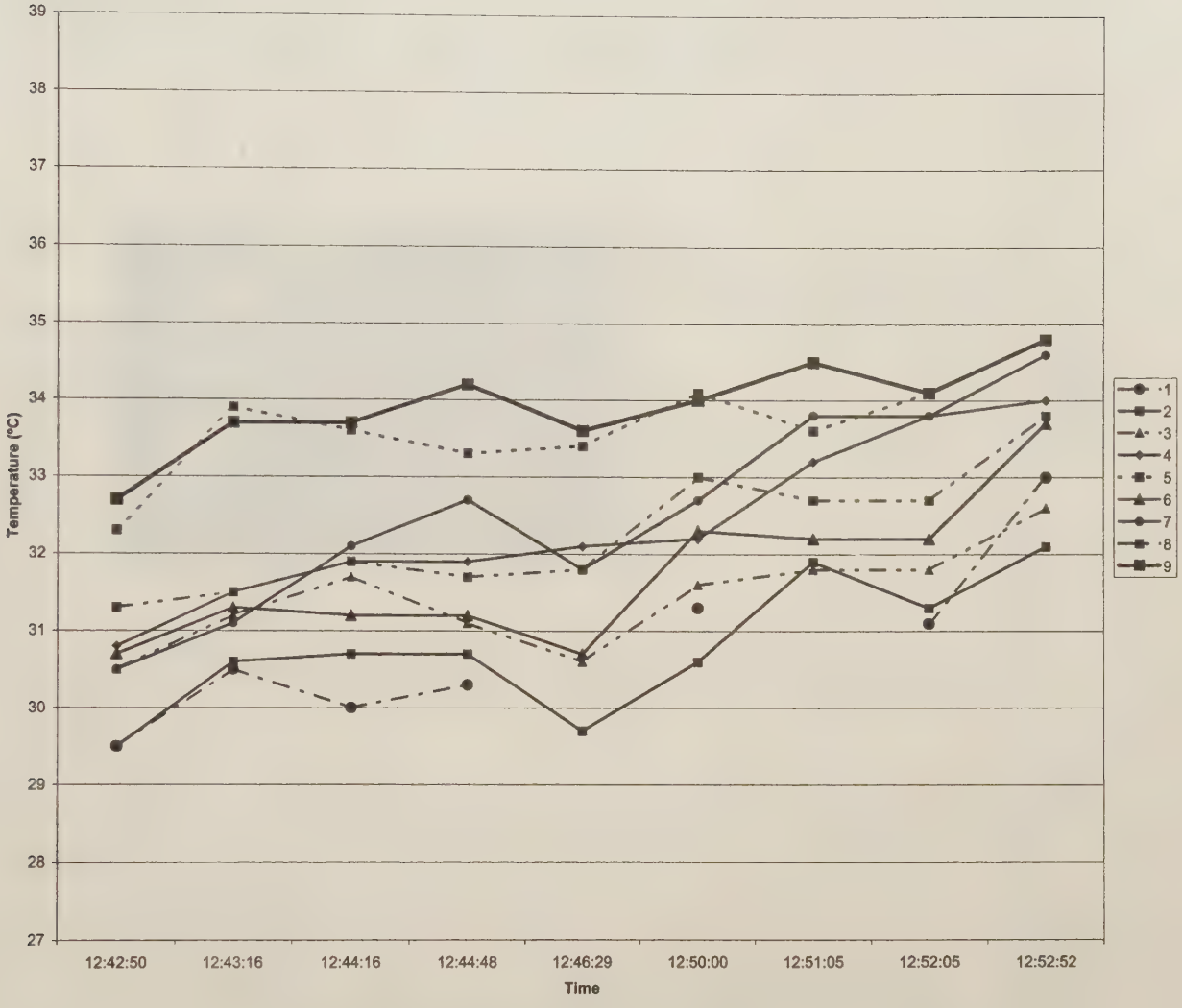
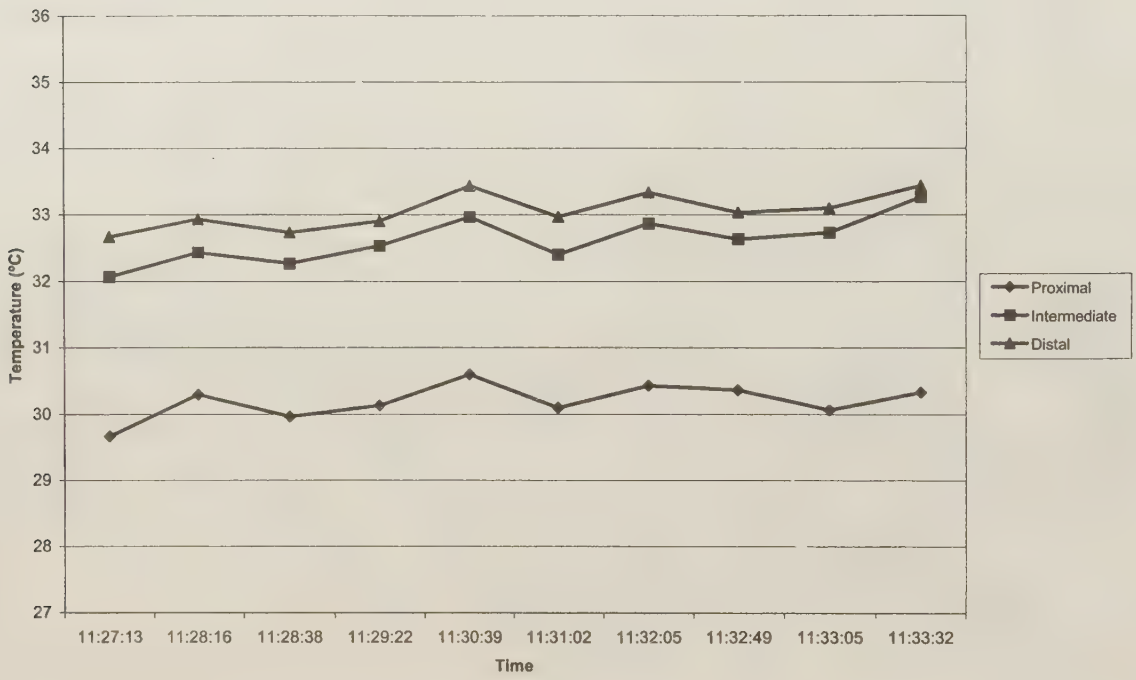


Figure 6. Mean values for the proximal, intermediate, and distal positions on the dorsal fin.
a. Thermal profile for FB 43.
b. Thermal profile for FB 196.

a.



b.

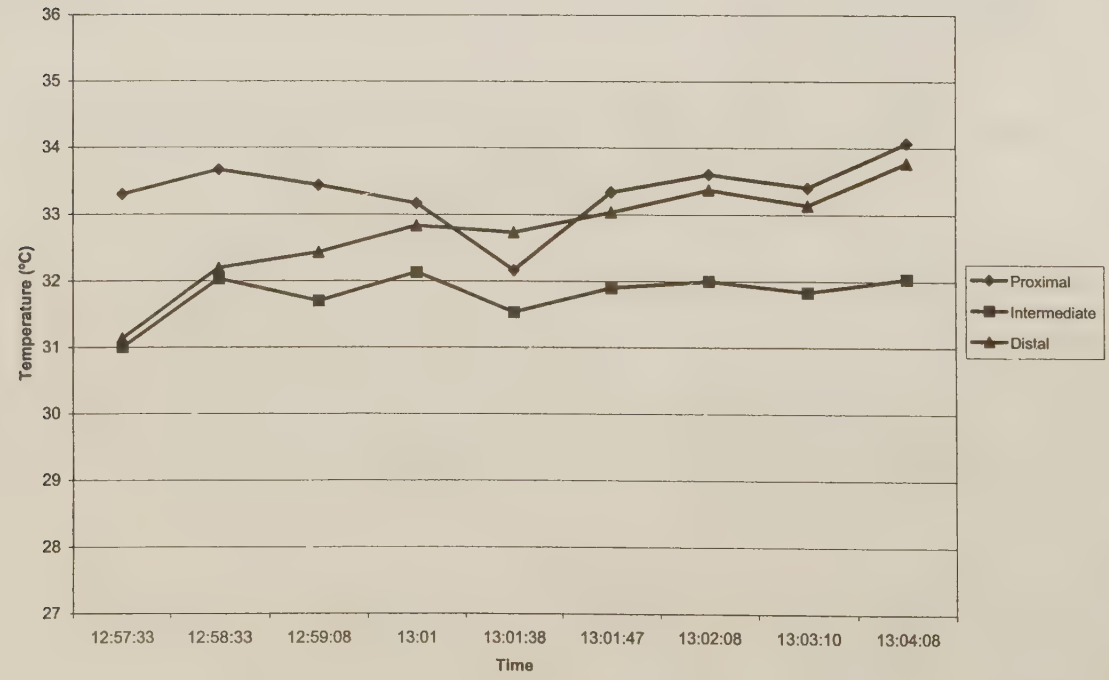
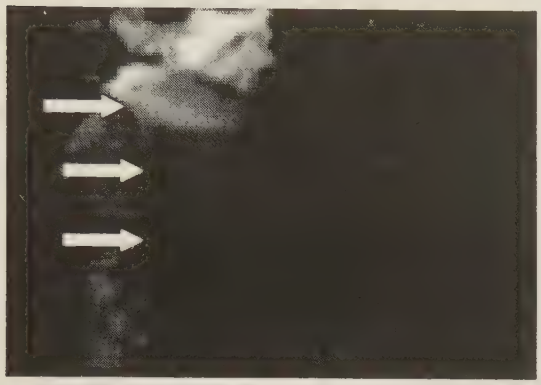


Figure 7. Thermal image and temperature data for FB 13.

a. Thermal image showing degrees of water effects. Top arrow indicates area of the fin not recently influenced by water (*i.e.* the warmest area of the fin). Middle arrow indicates area of fin most recently influenced by water (*i.e.* the coolest area of the fin). Bottom arrow indicates area of fin fairly recently influenced by water (*i.e.* the area of intermediate temperature).

b. Thermal profile of sites 1-9. Arrows indicate times of submergence in water.

a.



b.

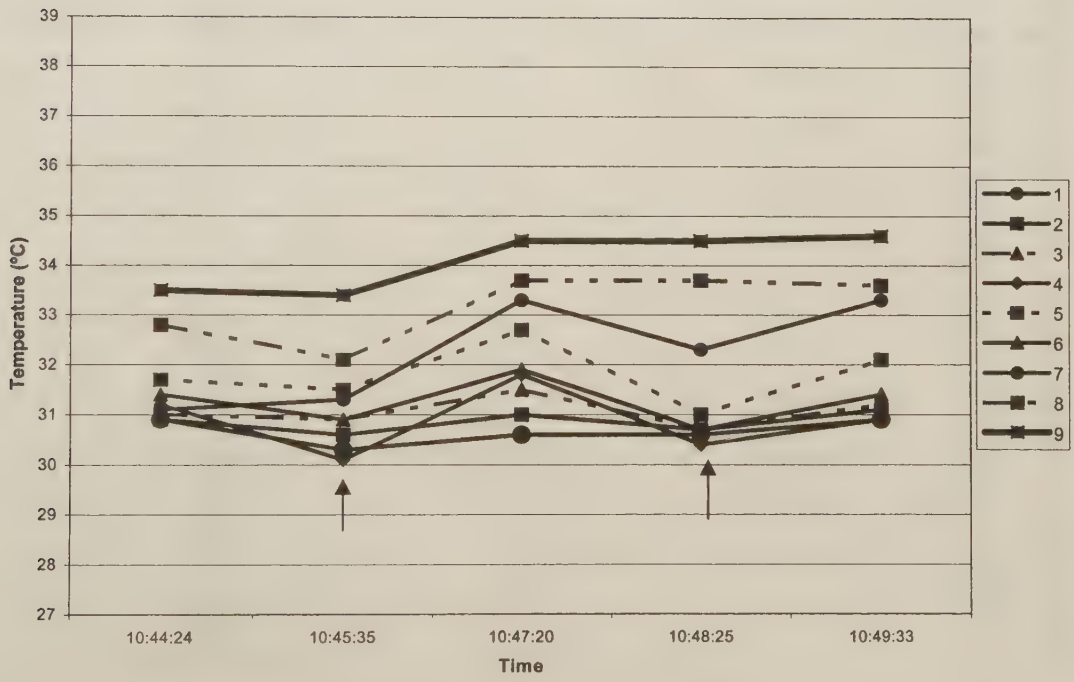
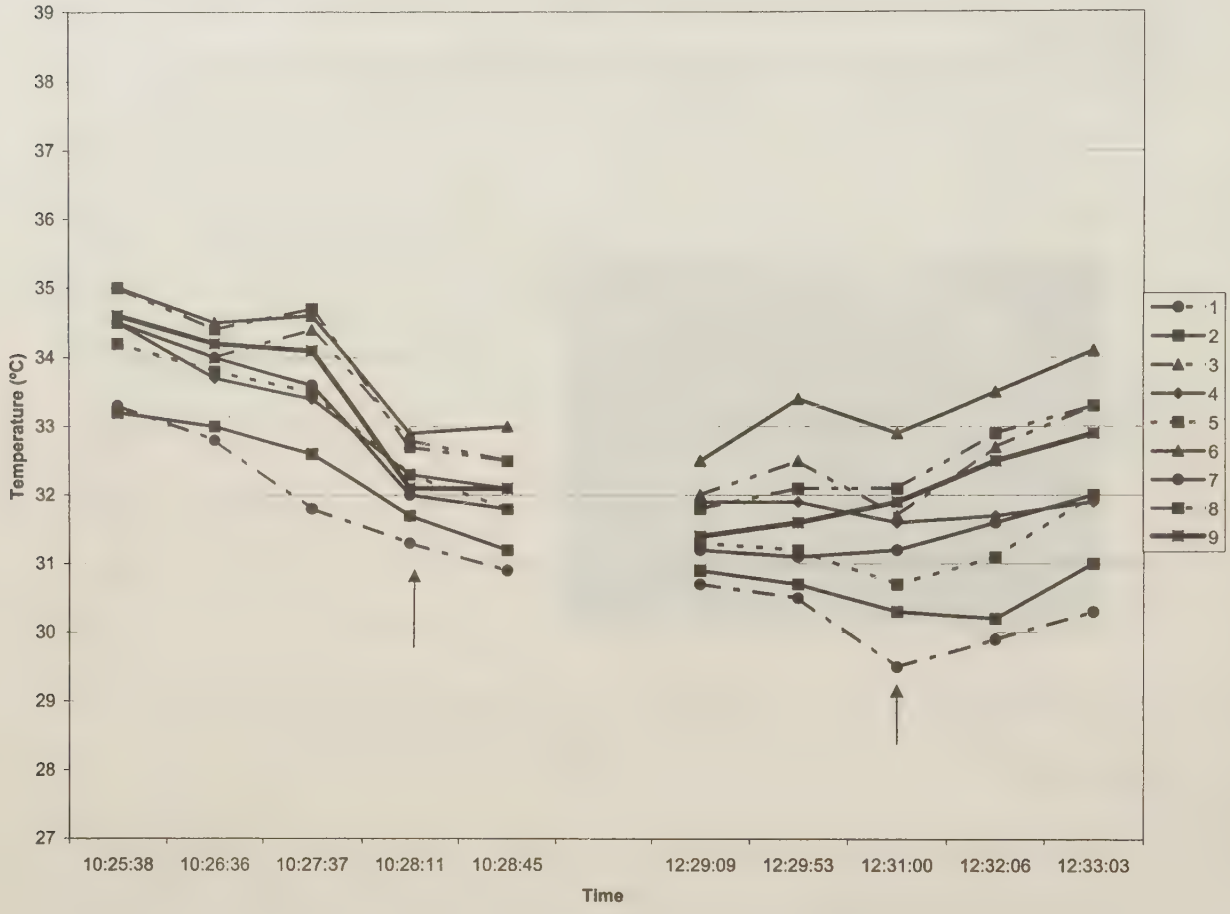


Figure 8. Thermal profile of sites 1-9 for FB 15. Arrows indicate partial/complete submergence in water.



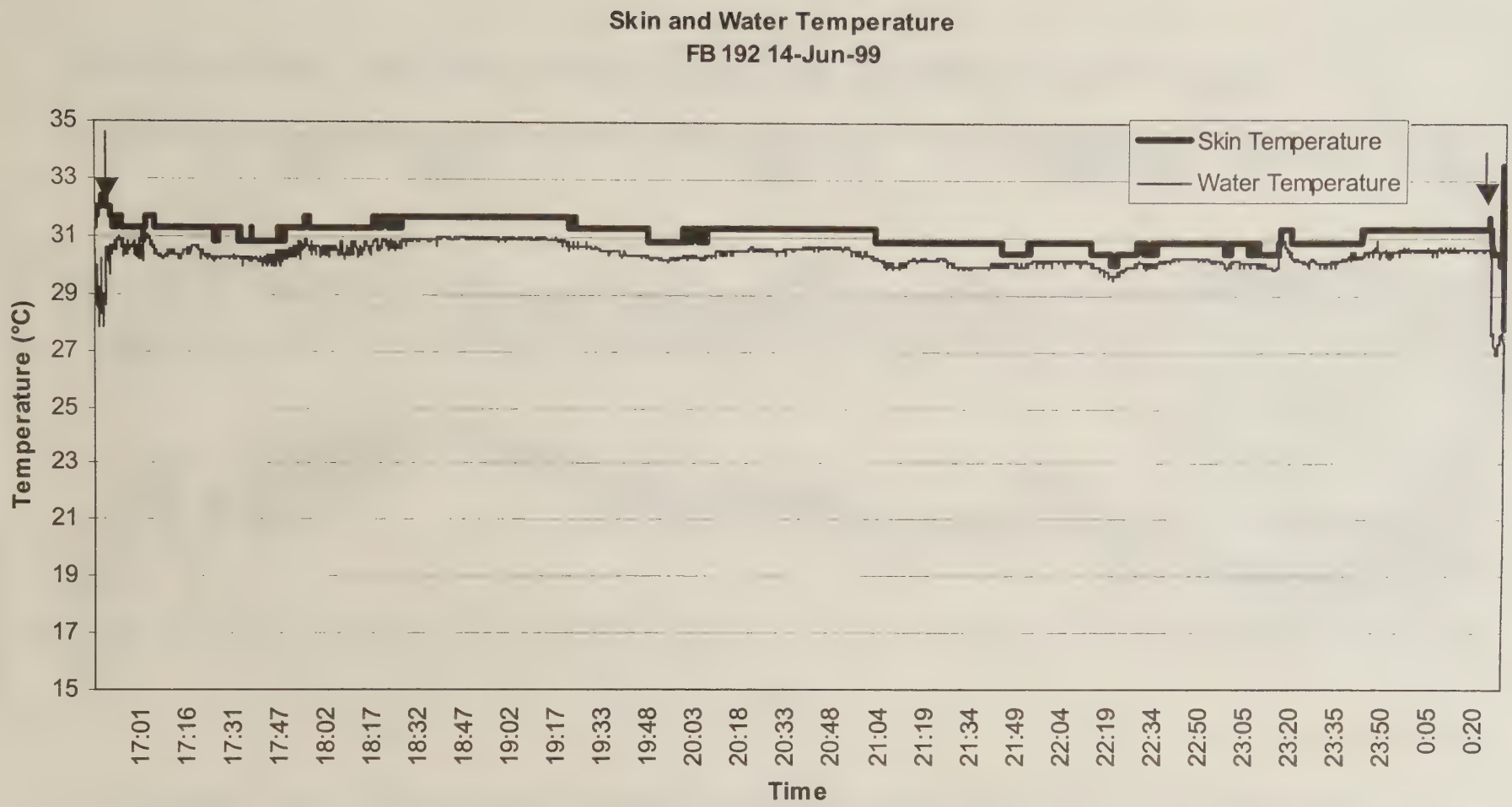


Figure 9a. Skin and water temperature for FB 192. Arrows depict times the thermal trac-pac was placed on fin and came off fin.

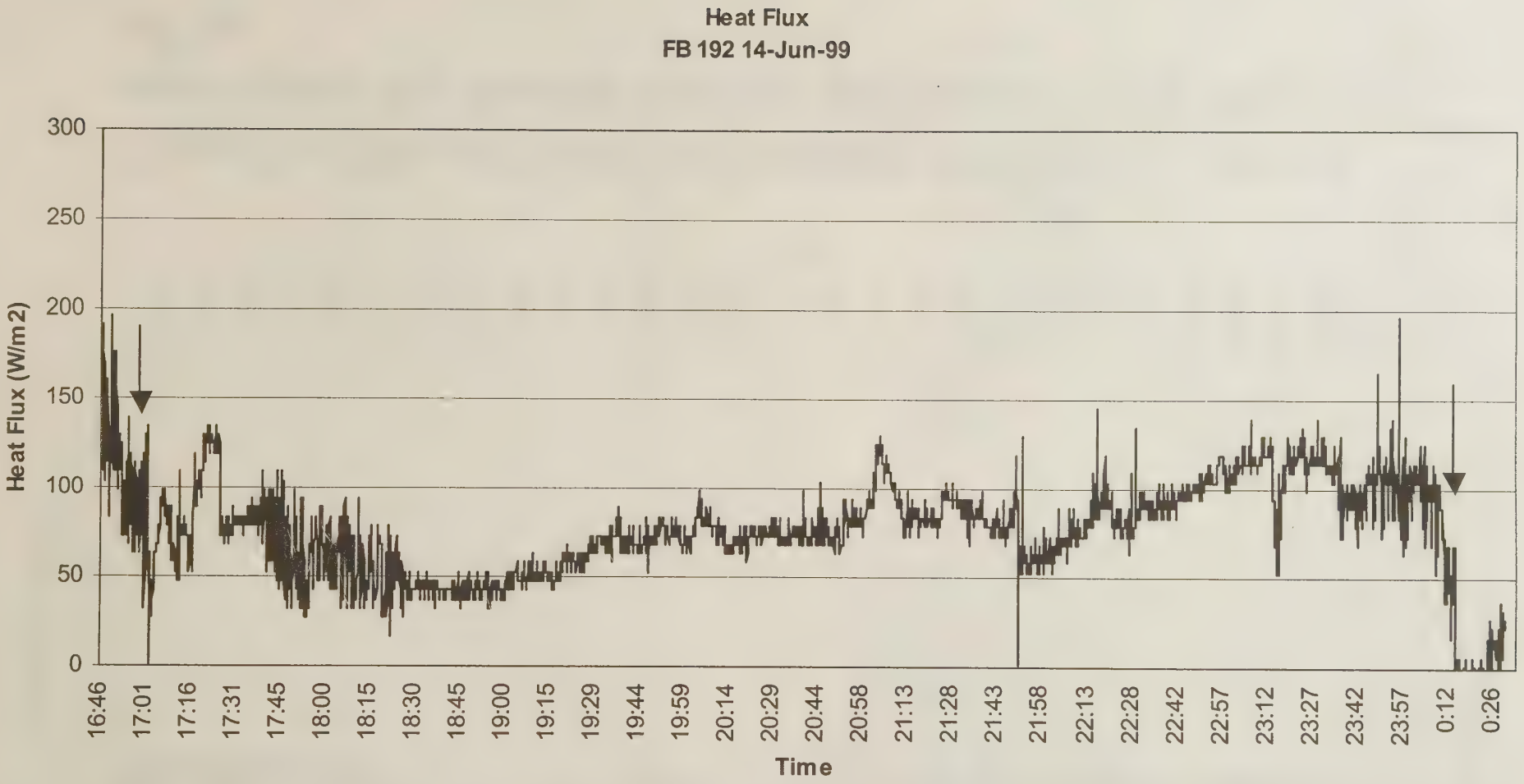


Figure 9b. Heat flux data for FB 192. Arrows depict times the thermal trac-pac was placed on fin and came off fin.

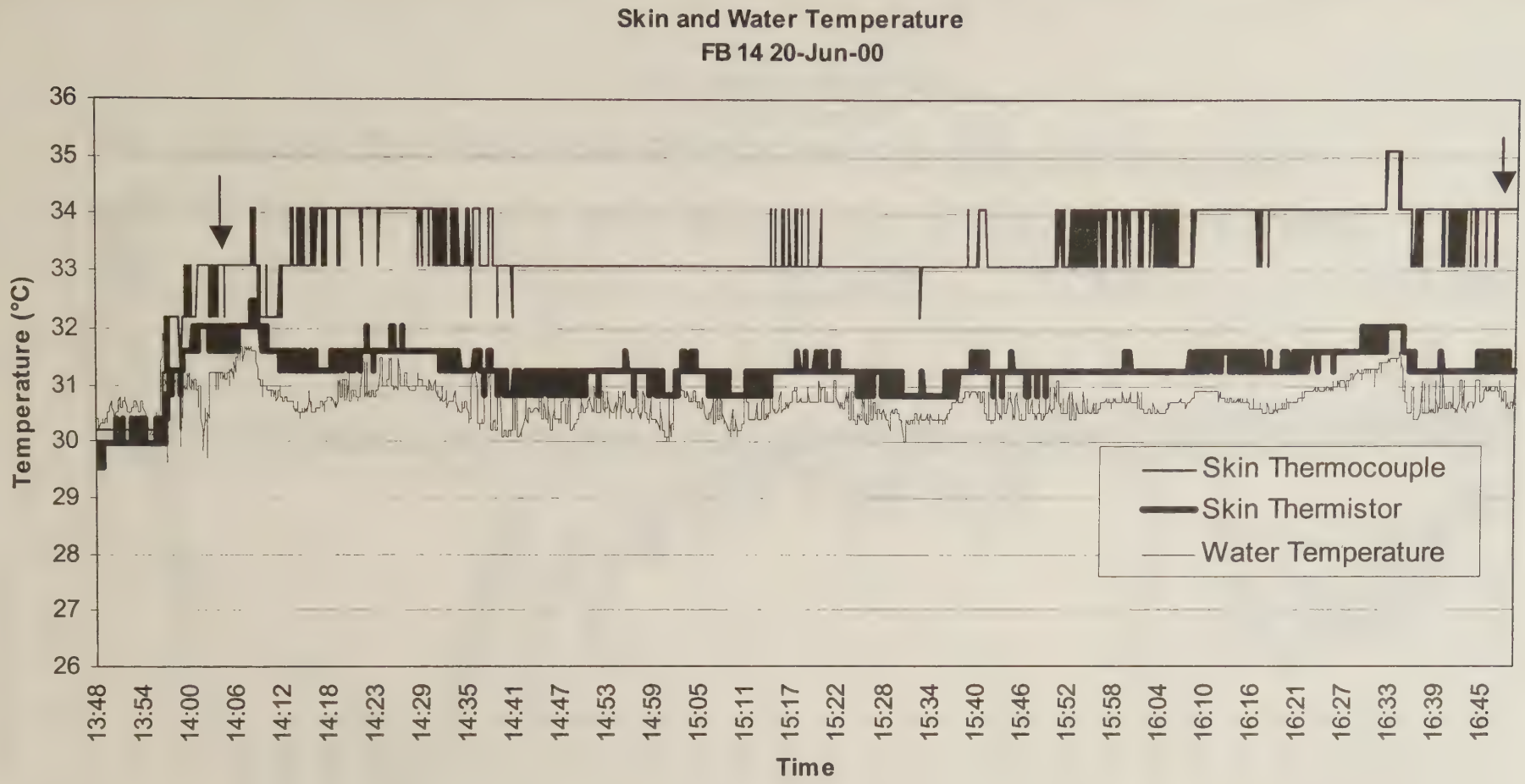


Figure 10a. Skin and water temperature for FB 14. Arrows depict times the thermal trac-pac was placed on fin and came off fin.

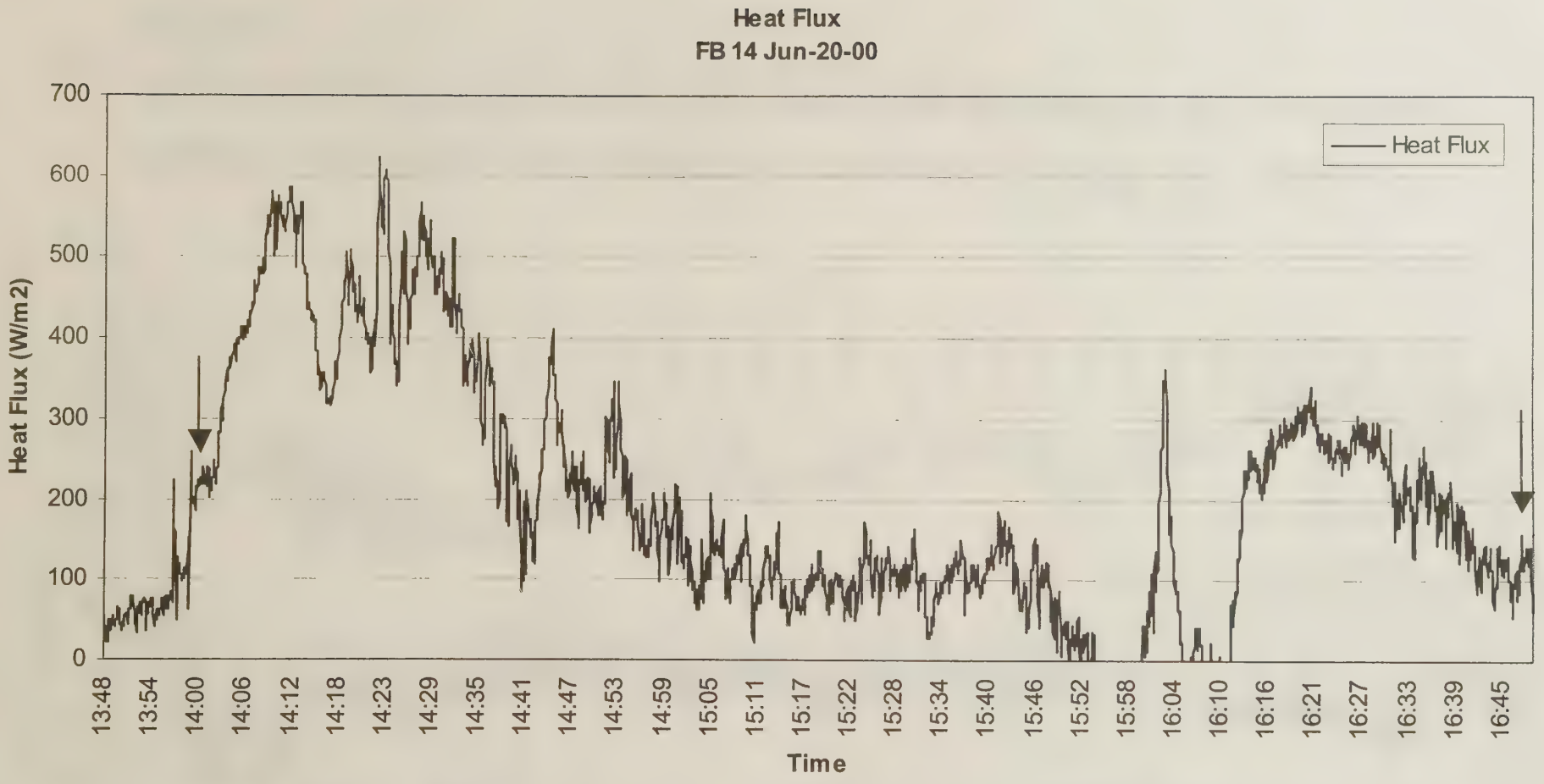


Figure 10b. Heat flux data for FB 14. Arrows depict times the thermal trac-pac was placed on fin and came off fin.

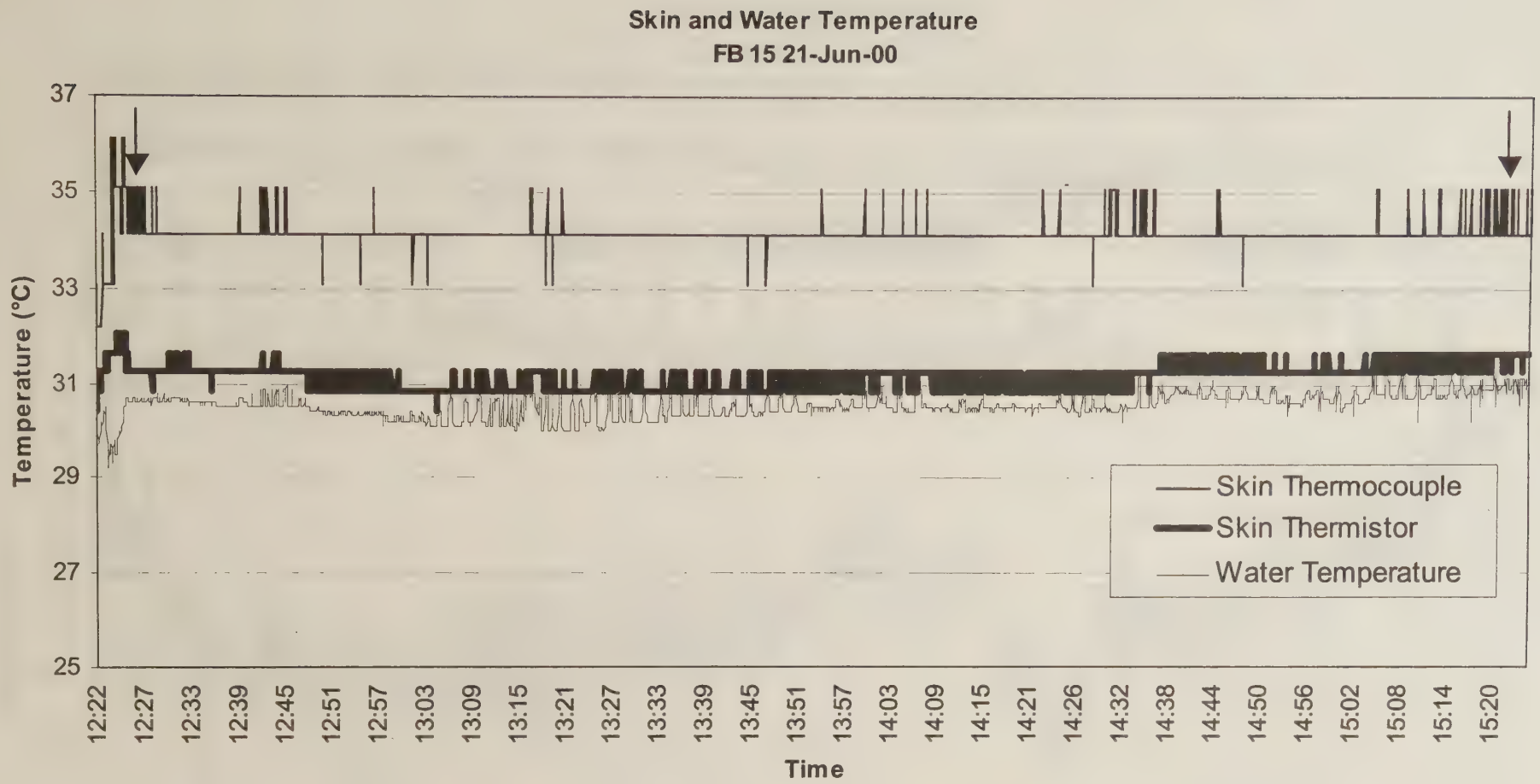


Figure 11a. Skin and water temperature for FB 15. Arrows depict times the thermal trac-pac was placed on fin and came off fin.

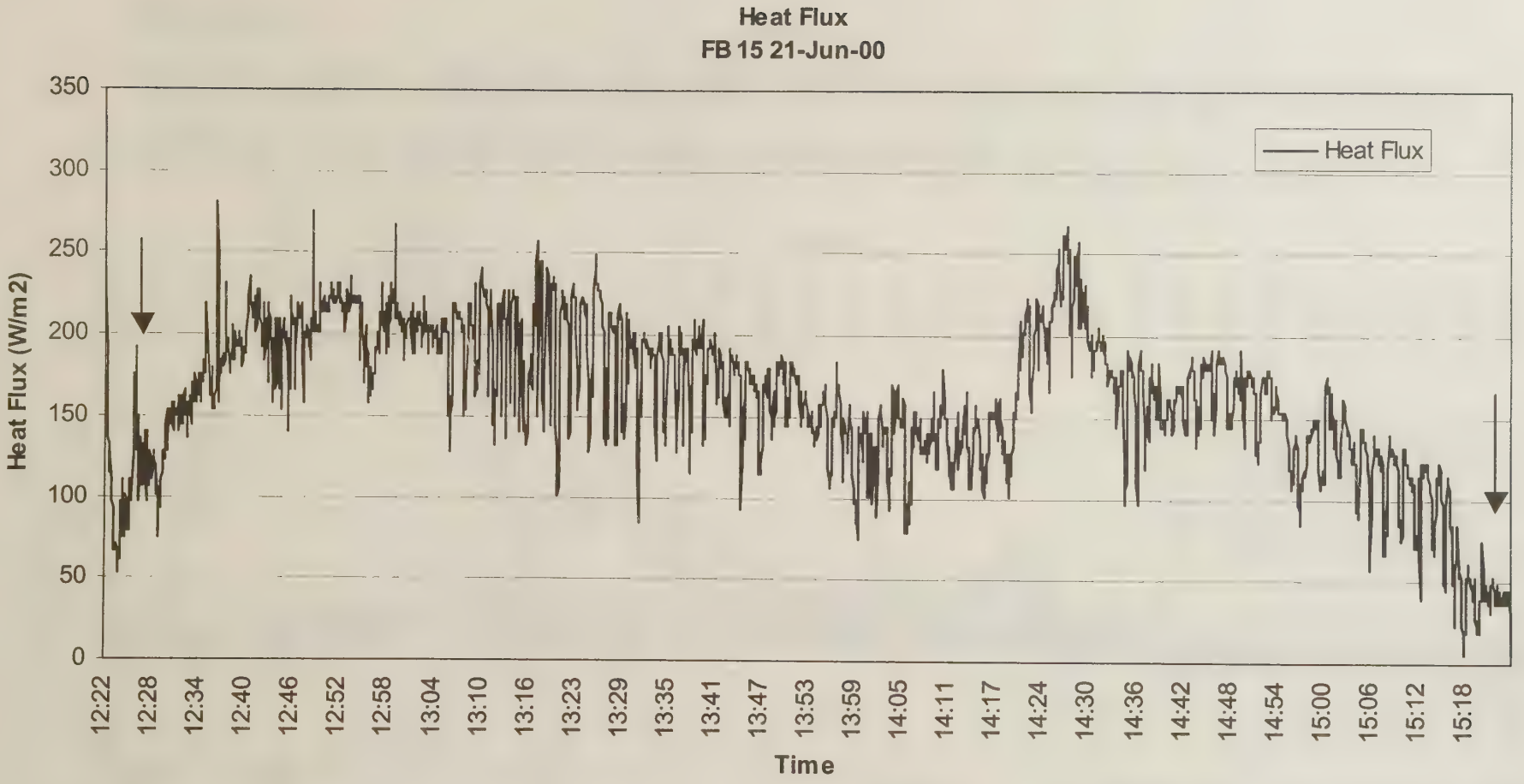


Figure 11b. Heat flux data for FB 15. Arrows depict times the thermal trac-pac was placed on fin and came off fin.

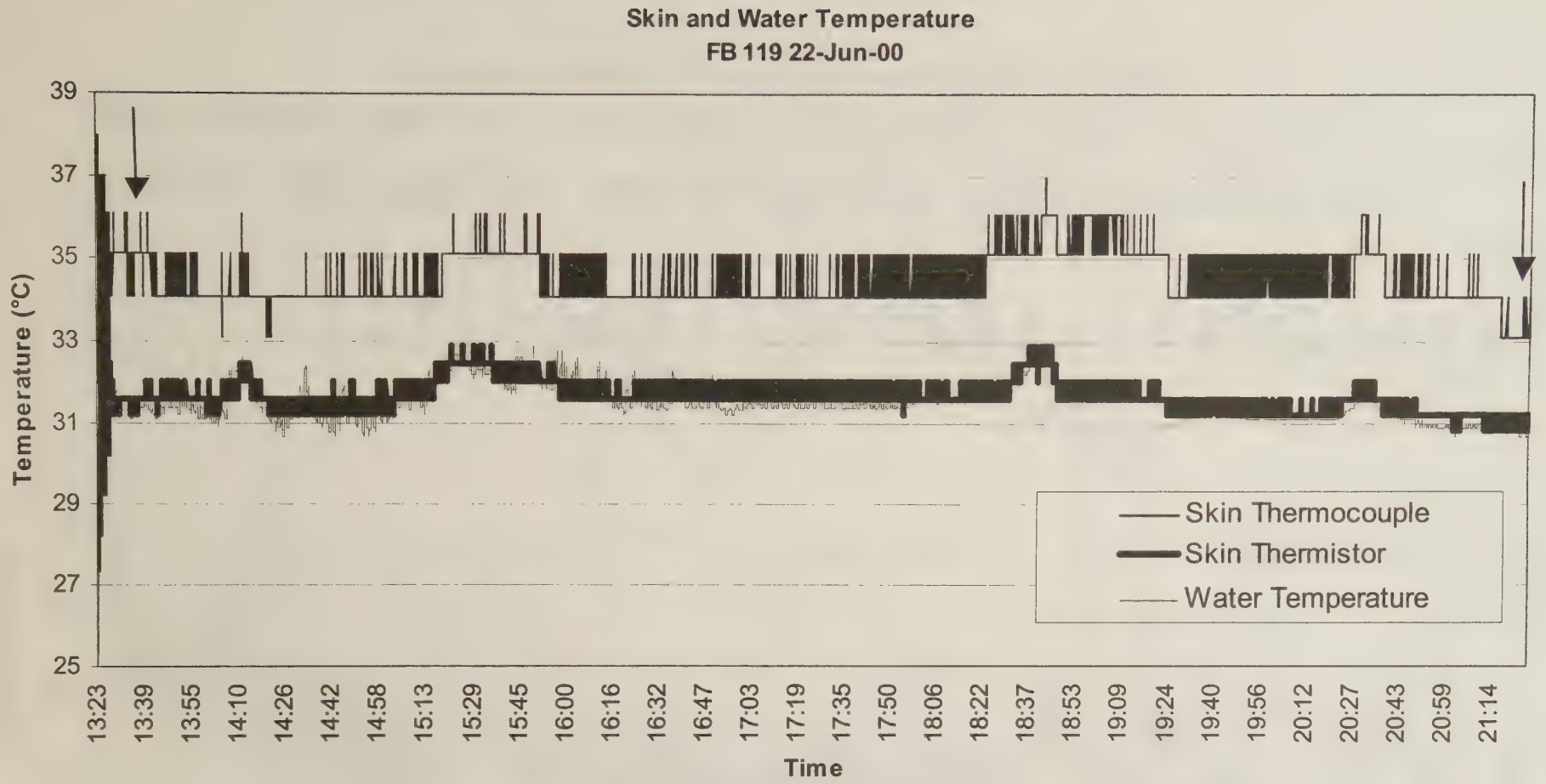


Figure 12a. Skin and water temperature for FB 119. Arrows depict times the thermal trac-pac was placed on fin and came off fin.

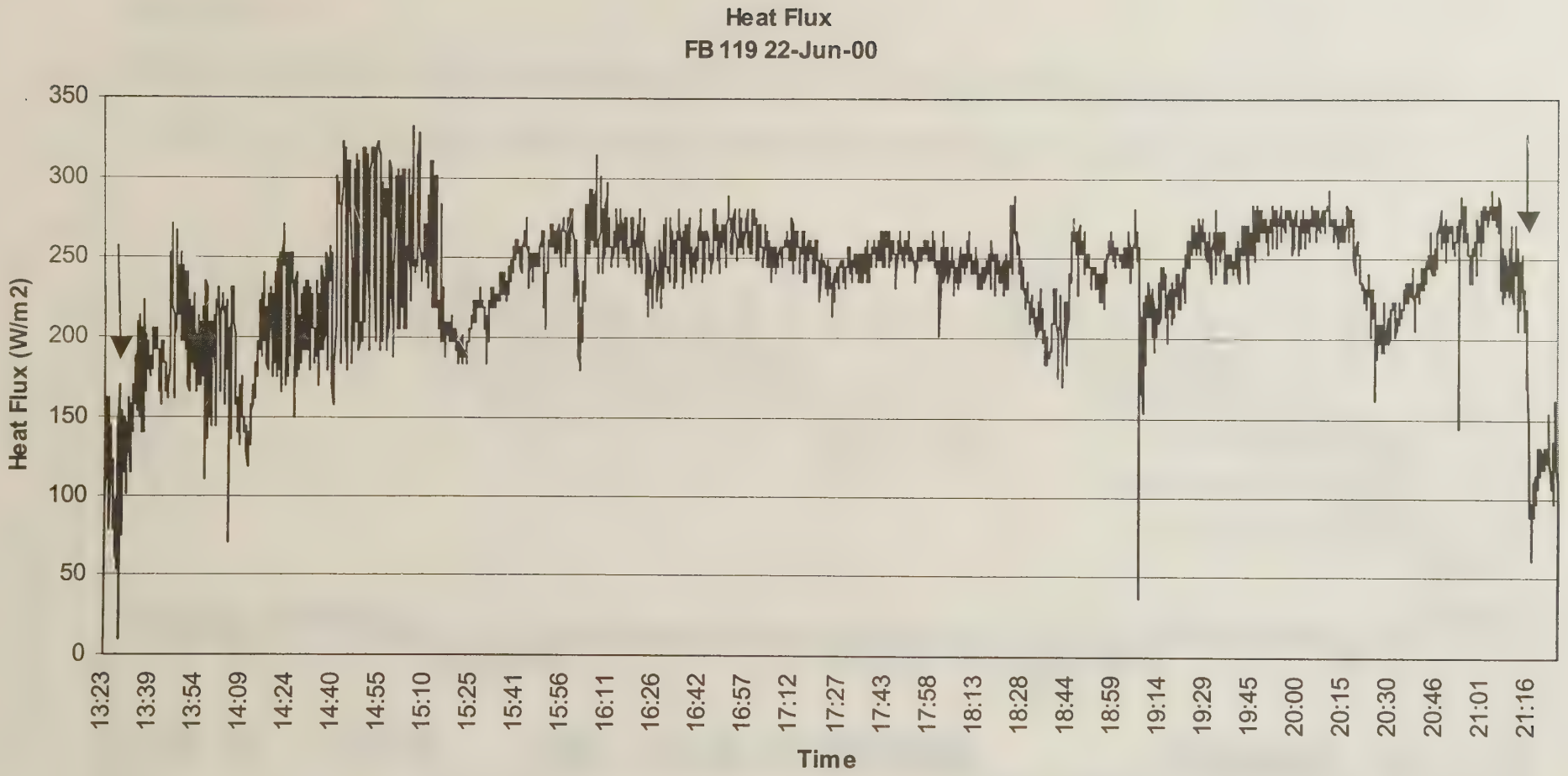


Figure 12b. Heat flux data for FB 119. Arrows depict times the thermal trac-pac was placed on fin and came off fin.

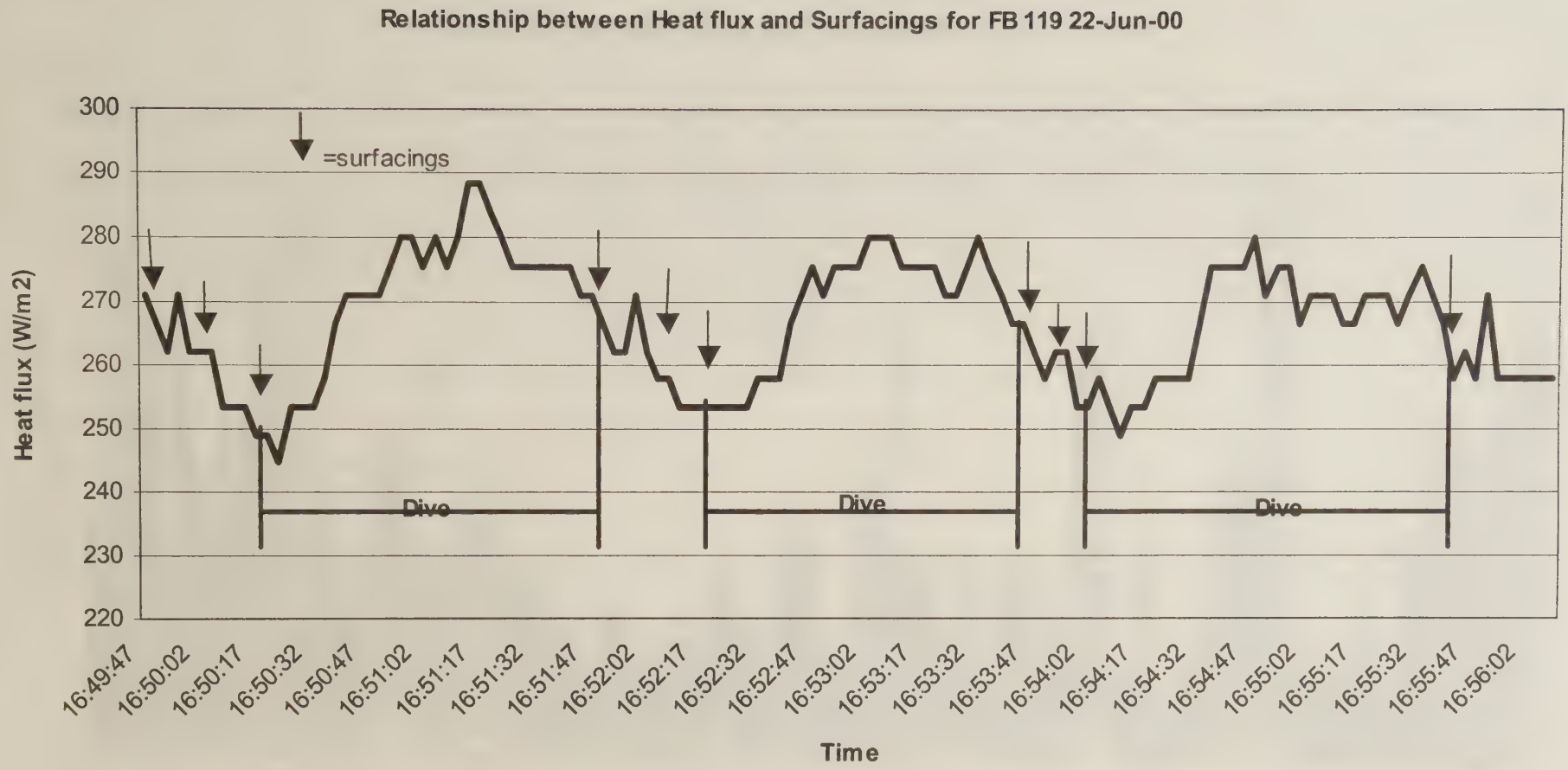


Figure 13. Fine-scale temporal pattern of heat flux data for FB 119. Note that heat flux increases during submergence and decreases at surfacing events.

Figure 14: Diving behavior of FB 63, June 11, 2001.

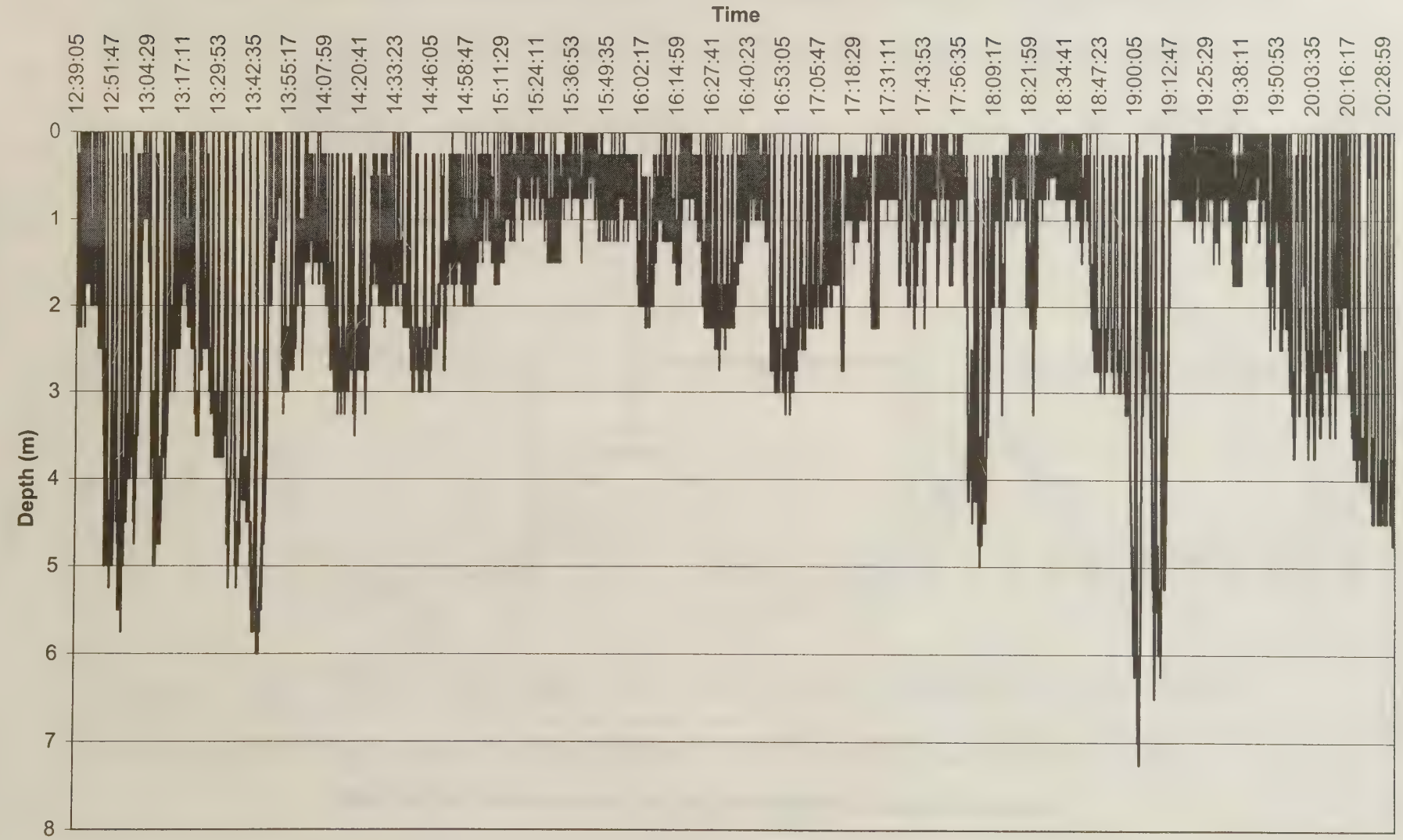


Figure 15. Skin temperature (°C) of FB 63, June 11, 2001.

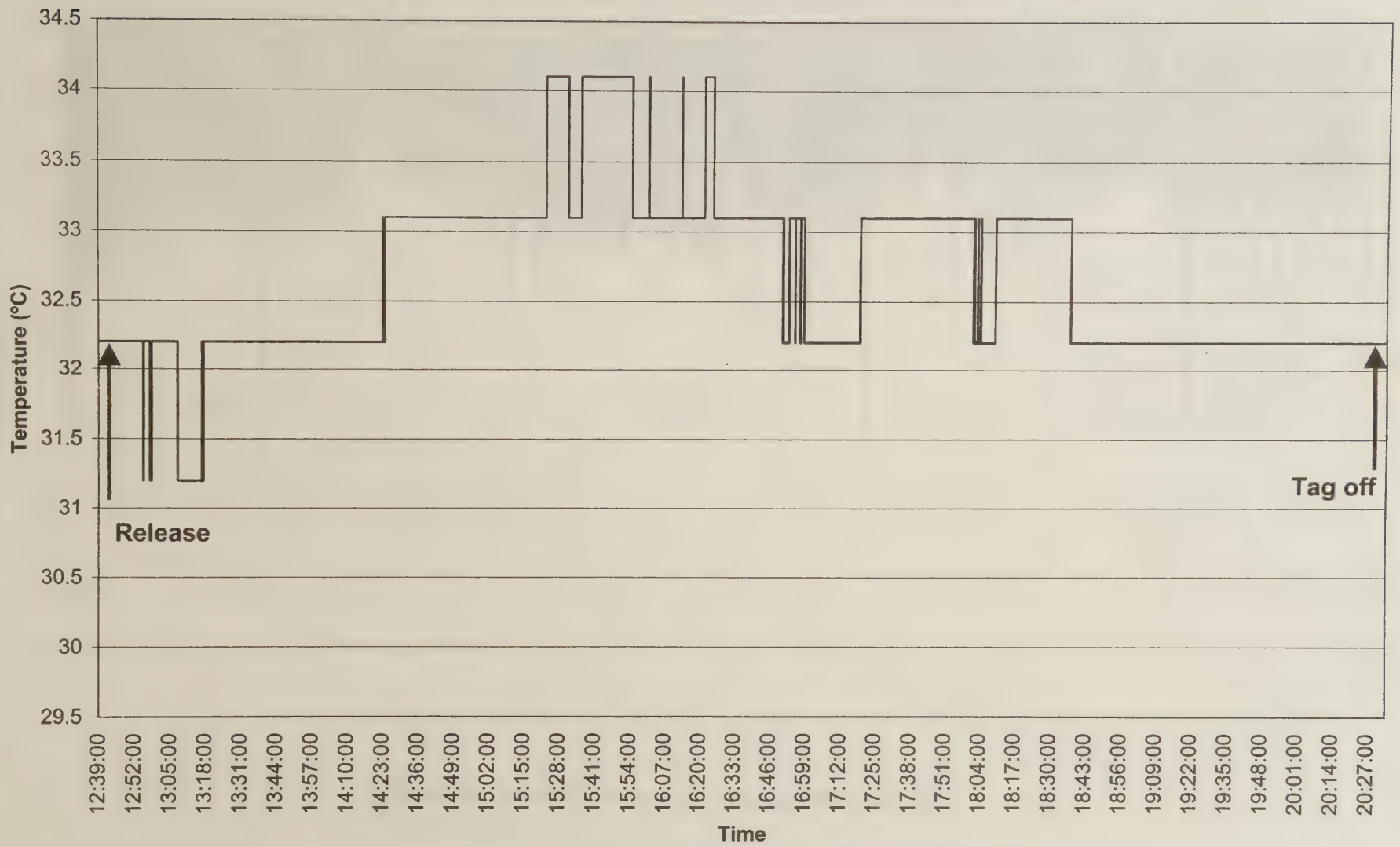


Figure 16. Velocity record for FB63, June 11, 2001.

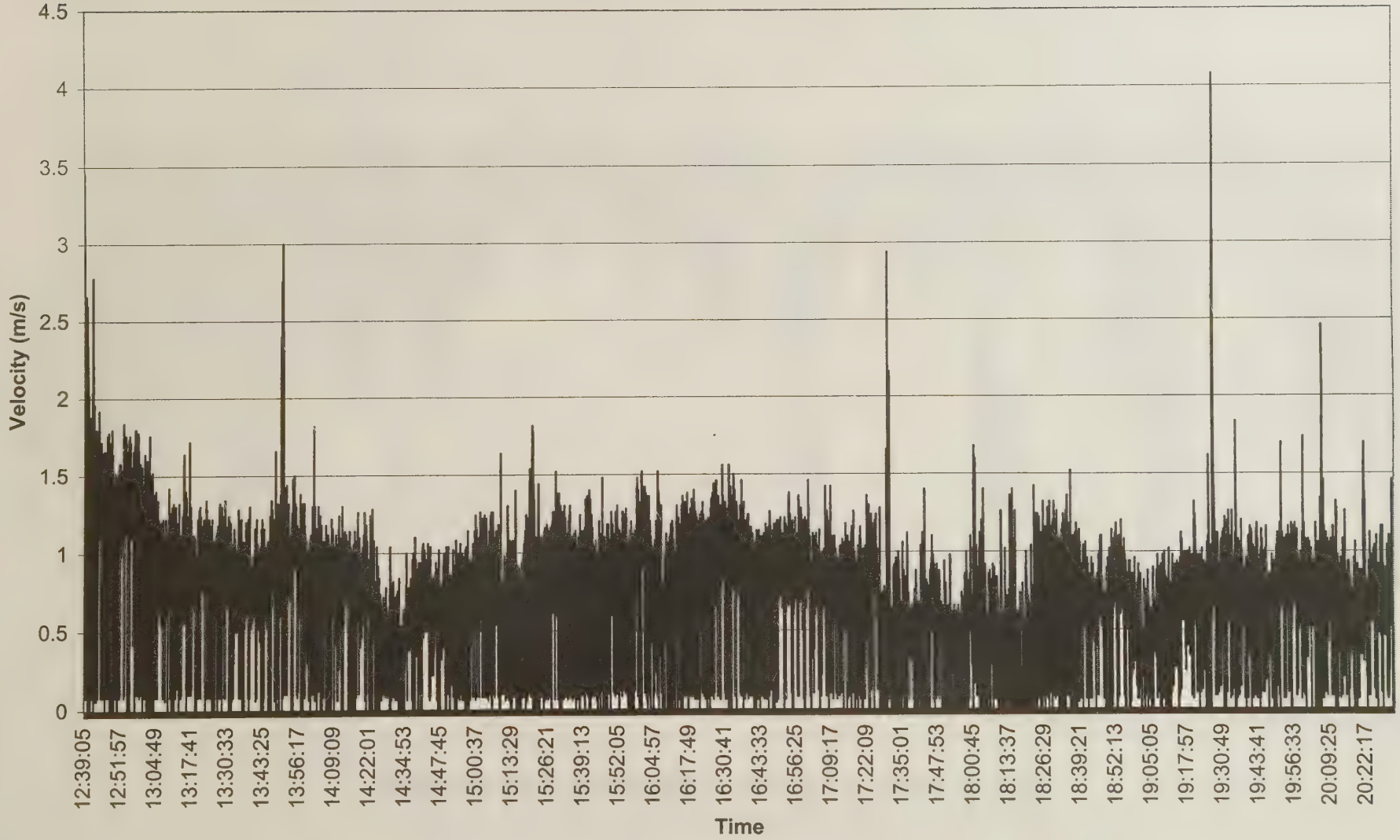


Figure 17. Water temperature record for FB63, June 11, 2001.

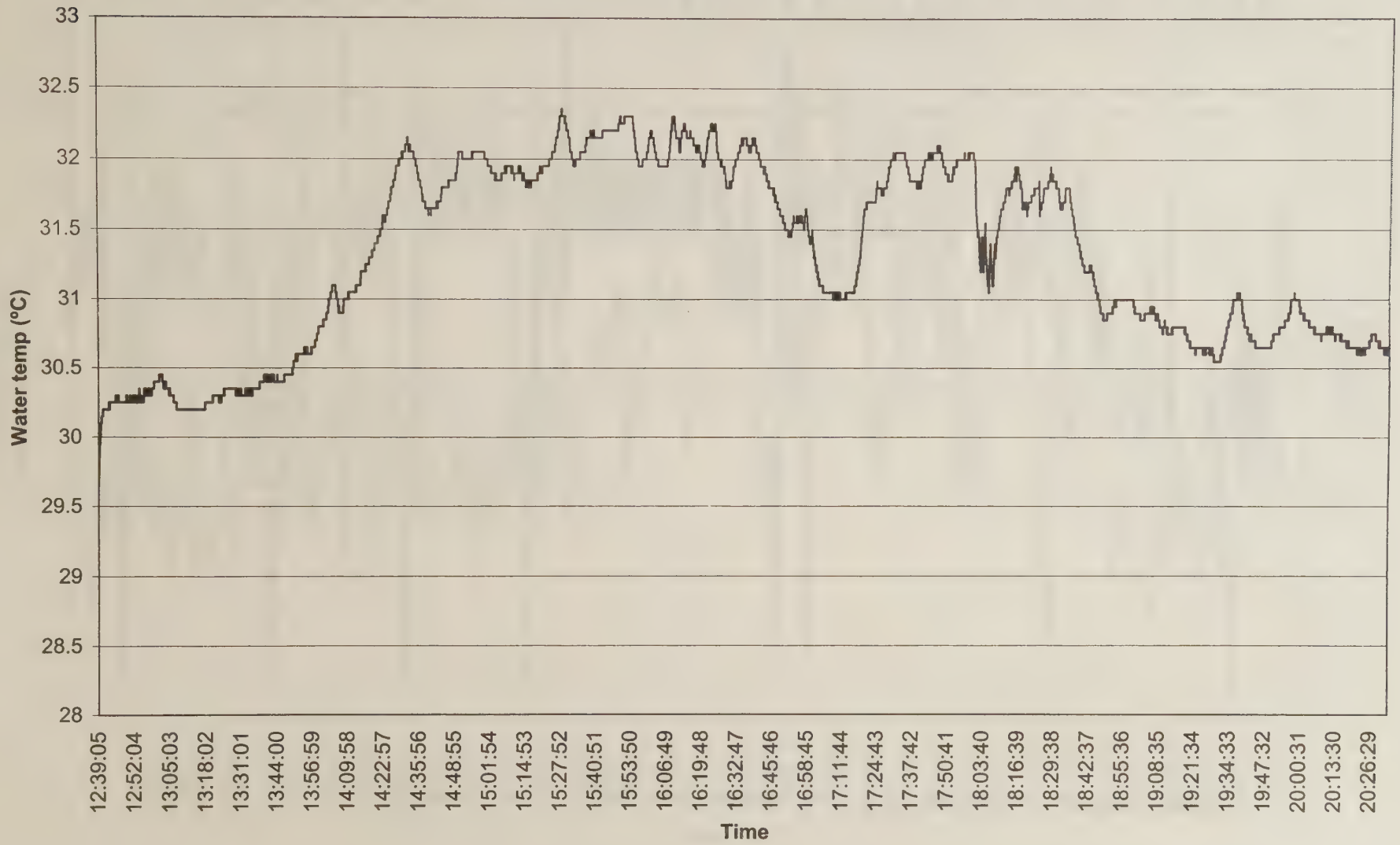


Figure 18. A 5-minute portion of the depth and velocity data from the trac-pac deployment for FB 63, 11 June 2001.

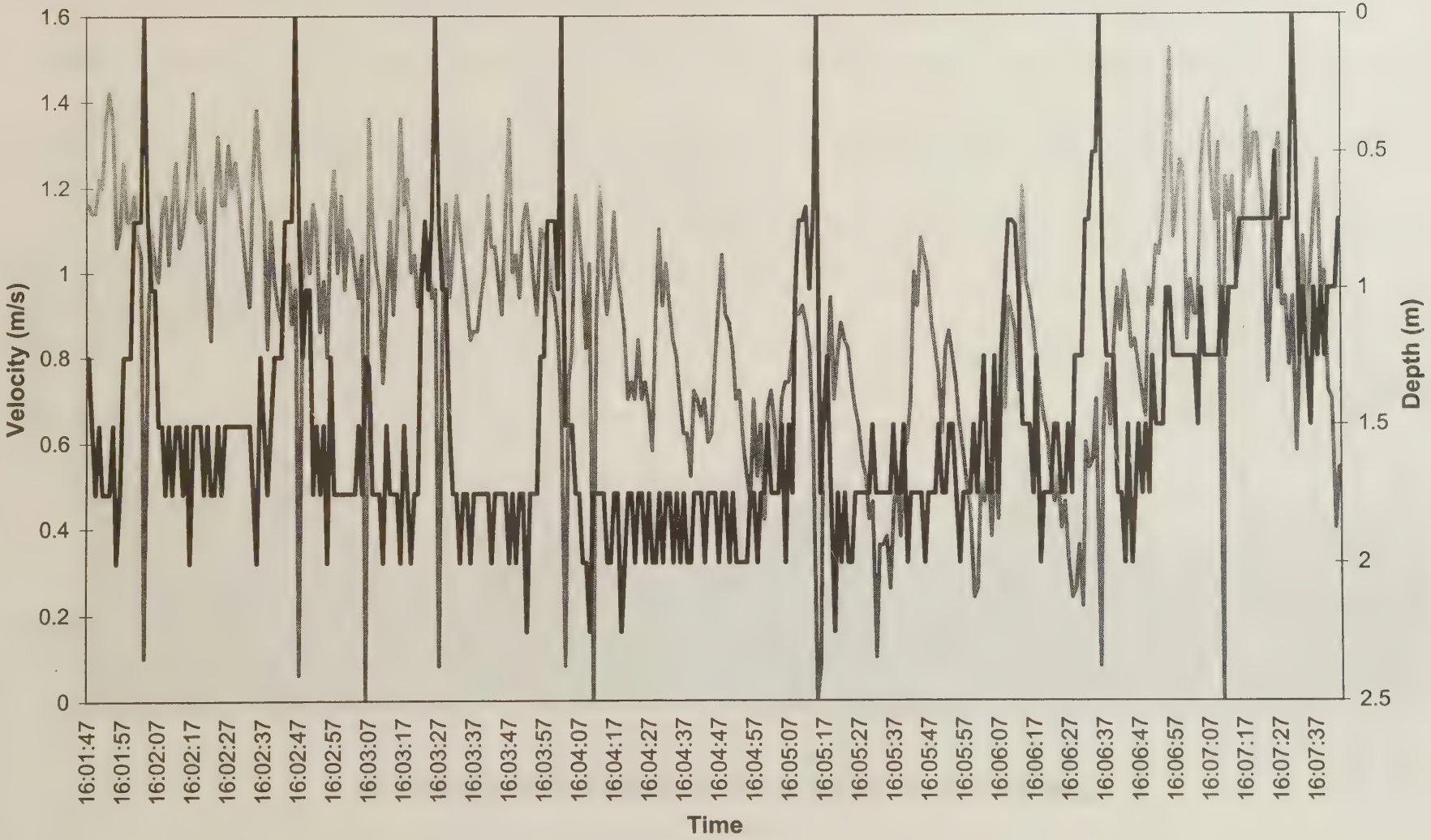


Figure 19. A 5-minute portion of the heat flux and skin temperature data from the trac-pac deployment for FB 63, 11 June 2001.

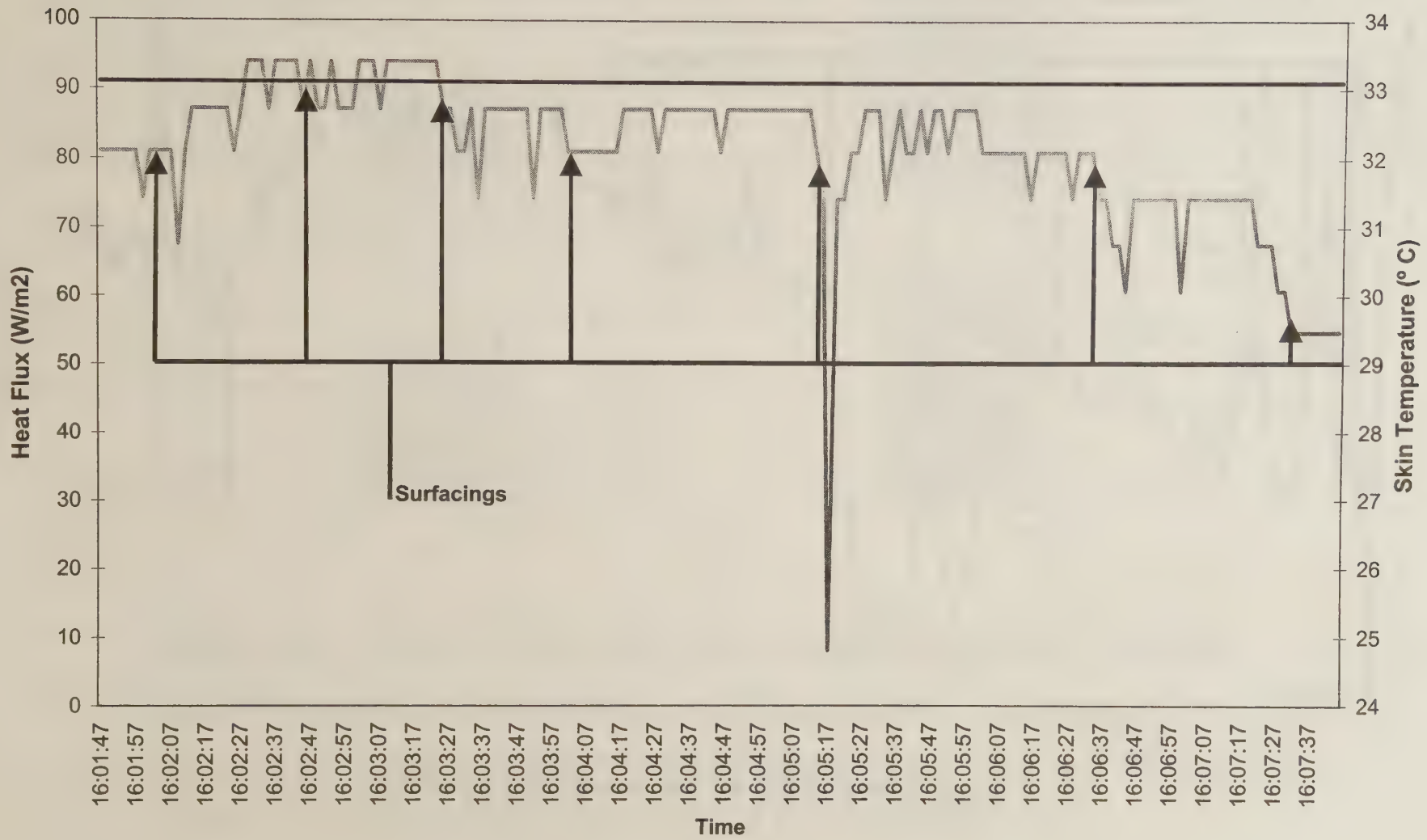
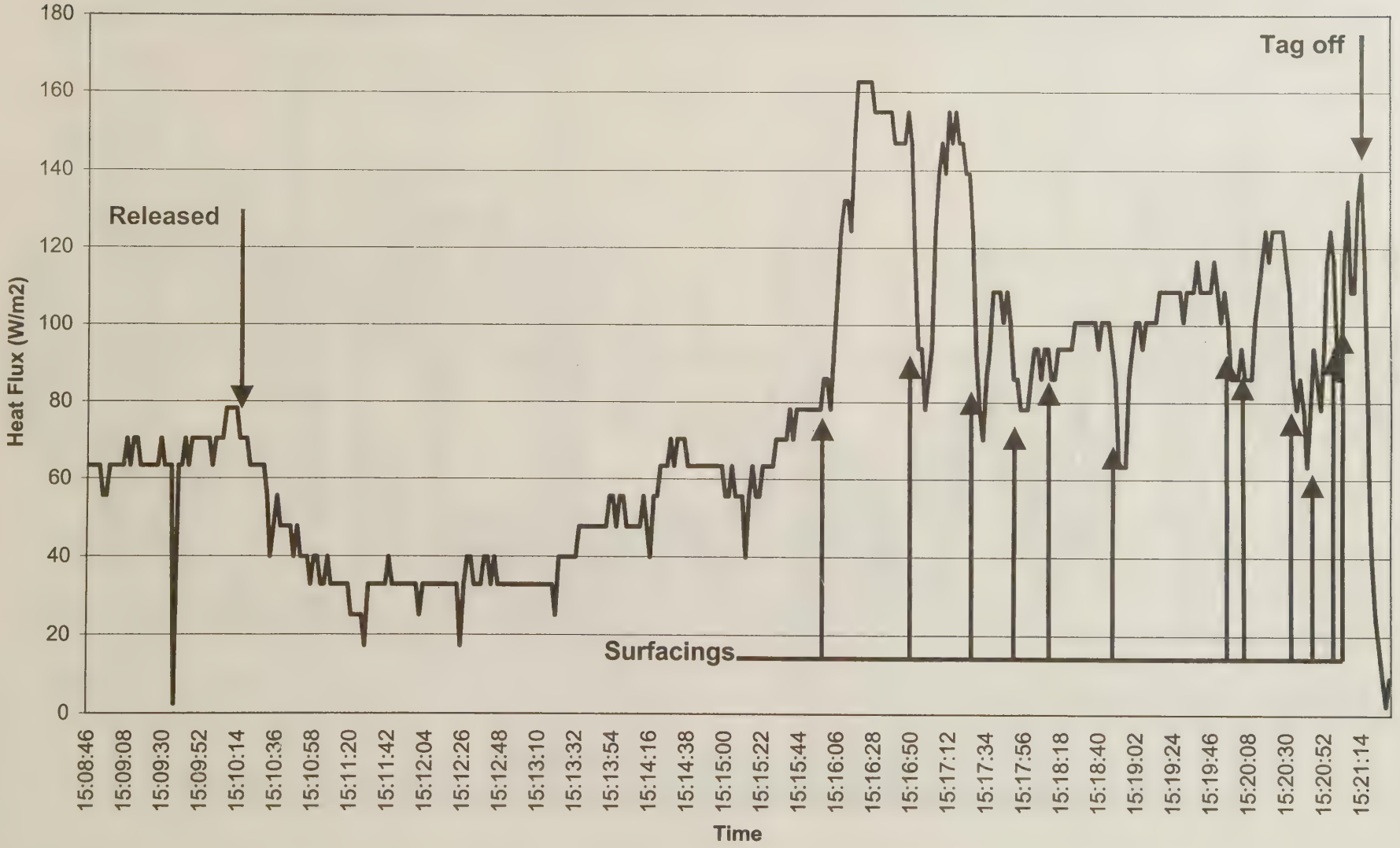


Figure 20. Heat flux record for FB113, 8 June 2001.



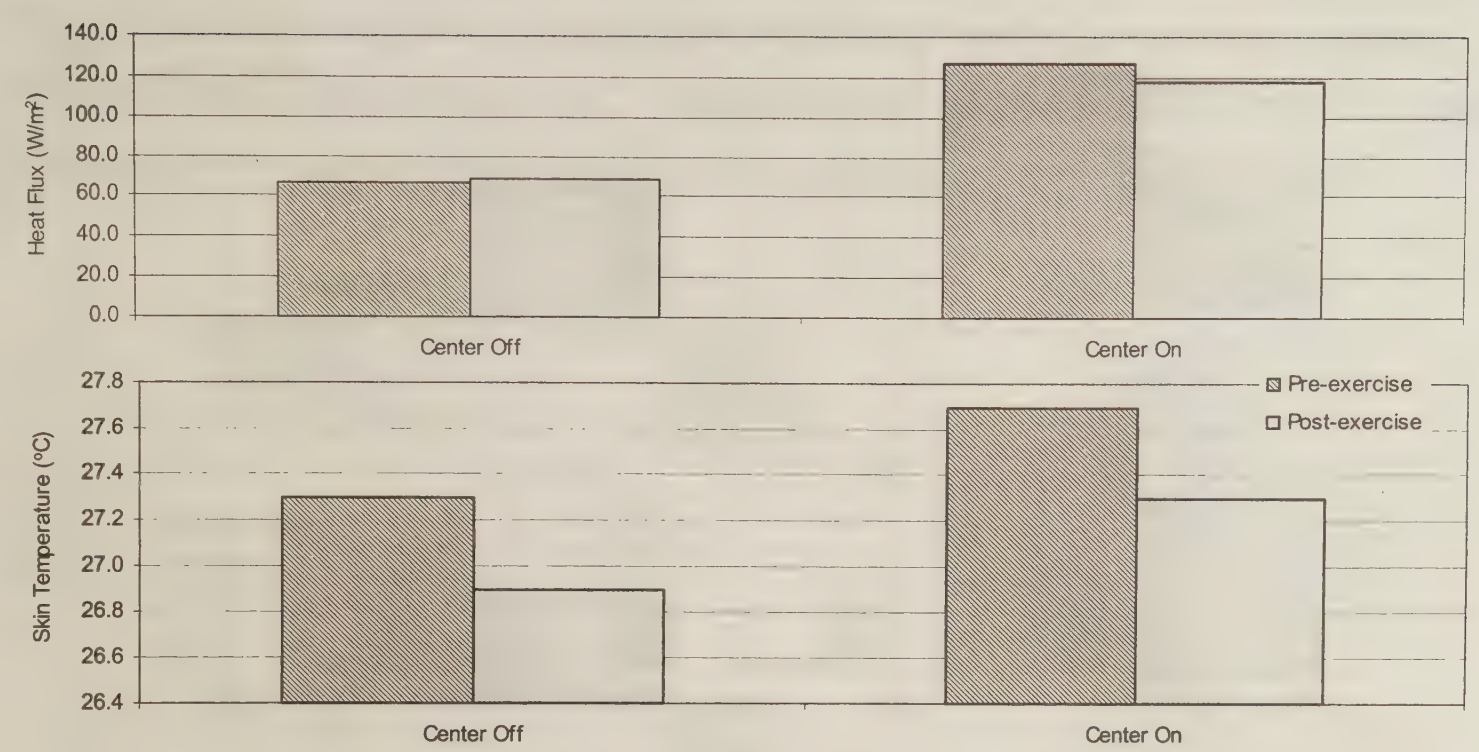


Figure 21. Heat flux and skin temperature for Hiiaka experimental session #1, mild exercise. (Center off = a center position on the fin, measured away from an obvious superficial vein. Center On = measured directly over a superficial vein.)

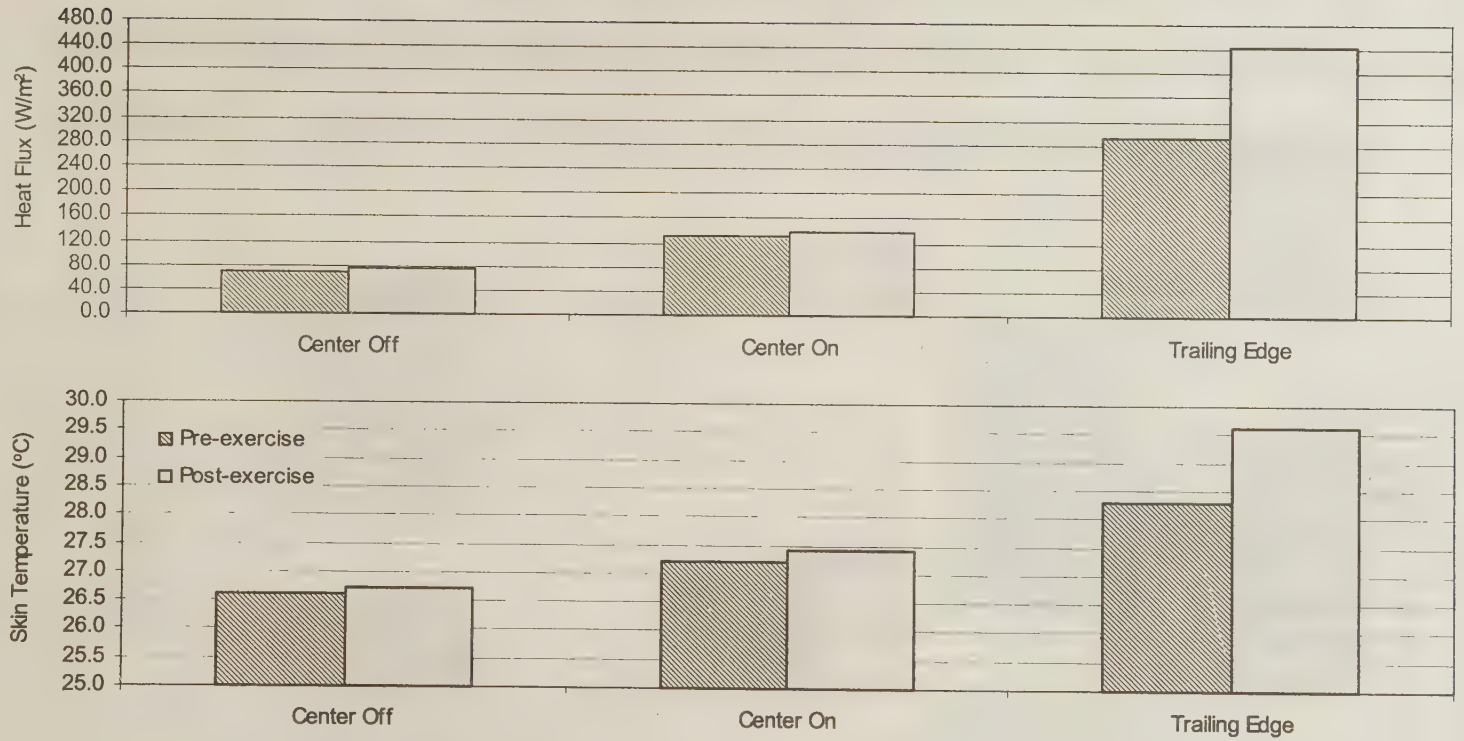


Figure 22. Heat flux and skin temperature for Hiiaka experimental session #2, medium to heavy exercise. (Center off = a center position on the fin, measured away from an obvious superficial vein. Center On = measured directly over a superficial vein. Trailing edge = caudal most region of fin.)

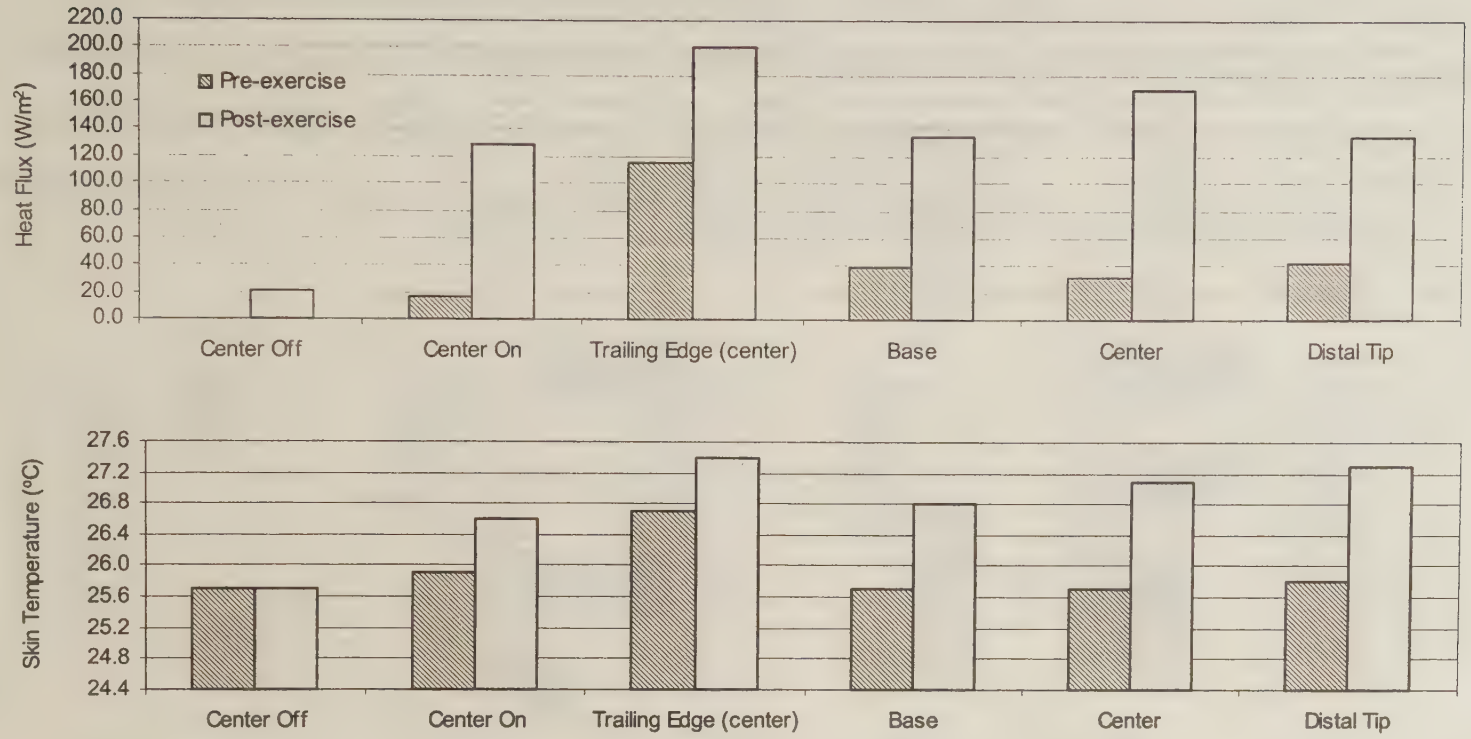


Figure 23. Heat flux and skin temperature for Hiiaka experimental session #4, medium to heavy exercise. (Center off = a center position on the fin, measured away from an obvious superficial vein. Center On = measured directly over a superficial vein. Trailing edge = caudal most region of fin. Base, center and distal refers to position along fin height.)

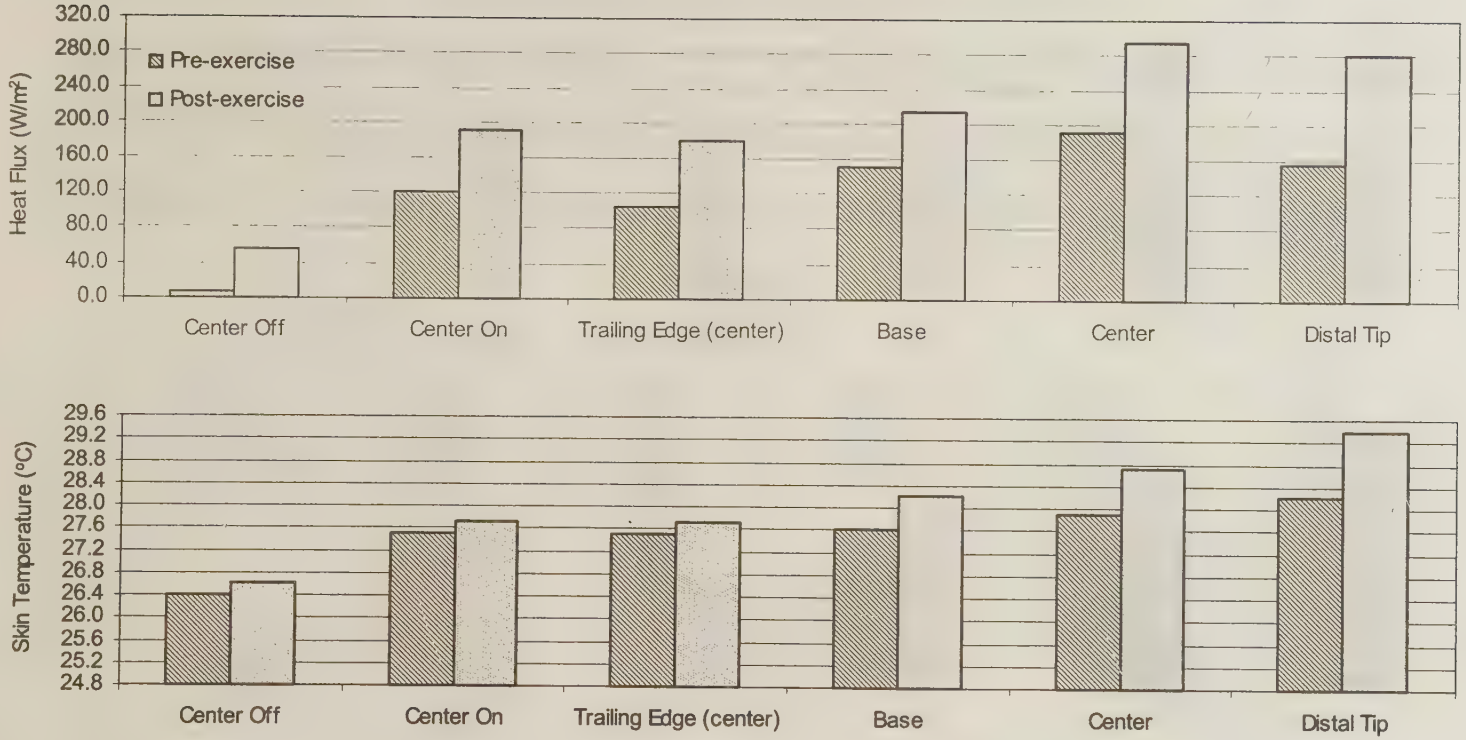


Figure 24. Heat flux and skin temperature for Hiiaka experimental session #5, heavy exercise. (Center off = a center position on the fin, measured away from an obvious superficial vein. Center On = measured directly over a superficial vein. Trailing edge = caudal most region of fin. Base, center and distal refers to position along fin height.)

Figure 25. Changes in heat flow in relation to type of activity for bottlenose dolphins. Three anatomical areas are compared, a) dorsal fin, b) fluke, and c) flank. Bars and vertical lines represent the mean change in heat flow + SEM from resting values measured immediately before activity sessions. Activity types are defined in the text. Numbers in parentheses are the total number of trials for each type of activity. Two male dolphins were used for all tests except stop-and-go activity, which used three adult females and one immature male.